NJDOT Bureau of Research

QUARTERLY PROGRESS REPORT

Project Title:	Reclaimed Asphalt Pavement In Hot Mix Asphalt
RFP NUMBER: 2009-01	**NJDOT RESEARCH PROJECT MANAGER**: Edward S. Kondrath
TASK ORDER NUMBER: 16	**PRINCIPAL INVESTIGATOR:** Yusuf Mehta, Ph.D, P.E. Rowan University
Project Starting Date: 1/1/2009 **Original Project Ending Date**: 12/31/2011	**Period Starting Date**: January 1, 2009 **Period Ending Date**: March 31, 2009

Task	**% of Total**	**% of Task this quarter**	**% of Task to date**	**% of Total Complete**
1. Comprehensive Literature Review	15	80	12	12
2. Assessment of the Variability of RAP Stockpiles in NJ	5	40	2	2
3. Sensitivity Analysis	20	0	0	0
4. Verification of Blending Charts	20	0	0	0
5. Evaluation of Laboratory Mixture Performance	20	0	0	0
6. Evaluation of Impact of Poor Quality Control Procedures	10	0	0	0
7. Conduct Life-Cycle Cost Analysis of Flexible Pavements with RAP	5	0	0	0
8. Final Report	5	0	0	0
TOTAL	100			14

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FIGURES

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RECLAIMED ASPHALT PAVEMENT IN HOT MIX ASPHALT

QUARTERLY PROGRESS REPORT – JANUARY 01-MARCH 31 2009

BACKGROUND AND RESEARCH PROBLEM:

New Jersey generates significantly more Reclaimed Asphalt Pavement (RAP) than it uses. For example, in Woodbridge, Bayshore Recycling Corporation has been generating and stockpiling RAP. The material in the existing pavement has value; if utilized effectively it will not only reduce the overall cost of the pavement but also develop environmentally friendly and sustainable pavements in the age of rapidly dwindling natural resources and quarries, especially in the North East.

Currently, the contractors are provided incentives for using high percentage of RAP, however, appropriate procedures to ensure quality control are not-in-place. There is a need to assess the impact of lack of quality control procedures on the mechanical properties of the mixture and subsequently conduct a detailed sensitivity analysis to develop protocol that can be followed during construction.

The performance of RAP in the mix will primarily depend on the following:

1. The interaction between RAP binder and the virgin binder

2. The aggregate gradation of the RAP and the virgin aggregates

3. The RAP mixture design.

RESEARCH GOALS AND OBJECTIVES:

The goals of this project are

a. to develop a thorough understanding of the properties of mixture and binder with higher percentages of RAP.

b. to explore the possibility of designing asphalt mixtures with high percentages of RAP approaching 50 % without compromising performance.

The specific objectives are to:
1. Determine from the existing literature and state of practice the challenges in characterizing binders with RAP, including blending charts, the extraction and recovery process, and testing methodology proposed in M320.

2. Conduct assessment of the variability of RAP stockpiles in the state of New Jersey. Develop a systematic way of rating the plants based on their quality control.

3. Conduct sensitivity analysis of blended binder properties with the change in percentages of RAP, and virgin binder properties.

4. Conduct extensive laboratory testing to quantify and verify the process of extraction and recovery, mixing and characterization for the binders and the RAP available in the state of New Jersey.

5. Conduct laboratory testing of mixtures to determine the degree of blending and evaluate the impact of various percentages of the RAP on unmodified and modified binders.

6. Evaluate the impact of poor quality control procedures on laboratory mixture performance and conduct a life cycle cost analysis of HMA with high percentages of RAP.

7. Develop specific recommendations to characterize modified and unmodified binder, and design mixtures with high percentages of RAP.

RESEARCH TASK

This section provides an update of each task.

TASK 1 – COMPREHENSIVE LITERATURE REVIEW

A comprehensive literature review of the state of practice of use of RAP in hot mix asphalt (HMA) was conducted. This literature review includes recent studies conducted by University of Illinois, University of Florida, Virginia Tech Research Council and University of Minnesota. The research team also attended the Transportation Research Board 88th annual conference and Rutgers annual asphalt paving conference to obtain invaluable information about the experimental protocol and issues associated with testing of RAP. Randy West (Director of NCAT at Auburn University) also provided a detailed active survey. All of this is incorporated in the detailed literature Review (attached as appendix A).

Development of "new" procedure of characterizing HMA at the plant is one of task of this project. Literature review of available test is shown in Appendix A2. The research team will also evaluate other test devices and procedures, including the ones that have been used in conjunction with the Superpave Gyratory Compactor. The research team will also coordinate with Randy West on the national effort being conducted on High RAP mixes.

TASK 2. - SURVEY AND GRADING SYSTEM FOR VARIABILITY WITHIN RAP STOCKPILES

A survey was created in order to learn about the stockpiling practices being used in New Jersey's asphalt plants. The questions were broken up into two categories: General Plant Questions and Stockpiling Practices. The questions under the general plant category gave information about the size and structure of the plant. The Stockpiling Questions gave information about the stockpiling practices of the plant. This included information on crushing and storage of RAP as well as important test procedures measuring the properties of the RAP binder and structure. The survey sheet used is attached in Appendix B1. A detailed summary of plant survey is given in Appendix B.

A grading system is also being produced to quantify the variability of RAP stockpiles within asphalt plants. This system focuses on how the binder properties, aggregate properties, and gradation of the RAP differ within a stockpile. The smaller the variability found in the RAP, the better the score the plant will receive, thus allowing them to use more RAP in roadways. This system being developed is going to be a combination of the methods used by NAPA, AASHTO, USDOT, and Maryland DOT in determining the allowable amount of RAP to use at plants ((MDOT, 1999), (Newcomb, 2007)). Their research has shown the importance of various aggregate and binder properties in mixtures with high RAP content. As of now, they have been able to rank the properties used in the grading system, which are gradation, CAA, FAA, stiffness, and asphalt content, from high to low. They have also given usual standard deviations for asphalt content and gradations which were also considered in the making of the grading system (Newcomb, 2007). The Maryland DOT has also been able to find a correlation between the standard deviation of asphalt content to allowable RAP percentage limits (MDOT, 1999). The proposed grading system will use this information to determine the allowable RAP limit. This grading system coexists with a tiered system that will ensure that the RAP being tested meets all current NJDOT specifications as well as acceptable limits for the standard deviation of aggregate and binder properties. This concept is explained in more detail in Appendix B2.

PROPOSED ACTIVITIES FOR NEXT QUARTER BY TASK

- ✓ Evaluate binder characteristic, moisture content and gradation of RAP sample from various plant.
- ✓ Prepare RAP mixtures for 15, 30 and 50% RAP content with PG 70-22 and PG 76-22.

LIST OF DELIVERABLES PROVIDED IN THIS QUARTER BY TASK

- ✓ Task 1

- Appendix A: Comprehensive literature survey on use of RAP with HMA

- Appendix A2: Literature review of simple plant test

✓ Task 2

- Appendix B: RAP plant survey
- Appendix B2: Plant grading system

PROGRESS ON IMPLEMENTATION AND TRAINING ACTIVITIES

Not scheduled

PROBLEMS/PROPOSED SOLUTIONS

Not scheduled

Total Project Budget	272453
Total Project Expenditure to date	0 (Contract approved on March 31st 2009)
% of Total Project Task completed	14%

COMPREHENSIVE LITERATURE SURVEY ON USE OF RAP WITH HMA

BY
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1. INTRODUCTION

In the early 1970s, when the oil embargo occurred, states and paving contractors began using alternate methods of cost reduction in asphalt concrete. Recycling during construction and rehabilitation is one of the several economic alternatives available for asphalt pavement. The Asphalt Recycling and Reclamation Association define four different types of recycling methods. They are hot recycling, hot in-place recycling, cold in-place recycling and full depth reclamation (Kandhal & Mallick, 1997).

In hot recycling, old pavement which requires rehabilitation is removed by milling, ripping, or crushing operation. This removed pavement material, reclaimed asphalt pavement (RAP), is combined with new material, such as virgin binder or rejuvenating agent, to produce hot mix asphalt (HMA) mixtures. This method of recycling results in a cost effective and environmental friendly method of recycling without affecting performance of pavement.

As per FHWA, one third of all HMA removed is recycled into HMA production (Publication No. FHWA-SA-95-060, 1995). This HMA containing RAP not only provides smooth, durable and safe roads, which is the motoring public's basic requirement, but also utilizes natural resources efficiently which saves taxpayers valuable money. The parking lot of Durham Bulls Baseball Stadium in North Carolina is an example of RAP's role in cost avoidance; it had saved 66000 cubic yard of aggregate by utilizing 25% of RAP in mix design (NAPA, 1998)

NCAT had carried out a survey (West, 2008) (Figure 1, Figure 2) to find the factors preventing higher RAP content in surface and non surface mixes. They found that state agency specification is a bigger concern than plant limitations, availability of RAP, variability of RAP to produce control mixes and fulfillment of volumetric properties of mix. Also 46% of NCAT survey responses indicate that they typically use the same percentage of RAP in surface and non surface mixes (16% and 20%). New Jersey state specification allows maximum 25% RAP in HMA base and intermediate layer and 15% for surface layer (NJDOT, 2007). This use of RAP is less than the amount generated which leaves behind a large quantity of unused RAP. Incorporation of high RAP in mix design is a feasible solution used by other states. This literature review has compiled information from other states regarding the performance of RAP mixes, the Superpave mix design using RAP with and without rejuvenators, and the performance RAP mixes and factors involved in RAP mix design such as variability, stockpiling, sampling, RAP aggregate characteristic, method of extraction of RAP binder and RAP binder properties.

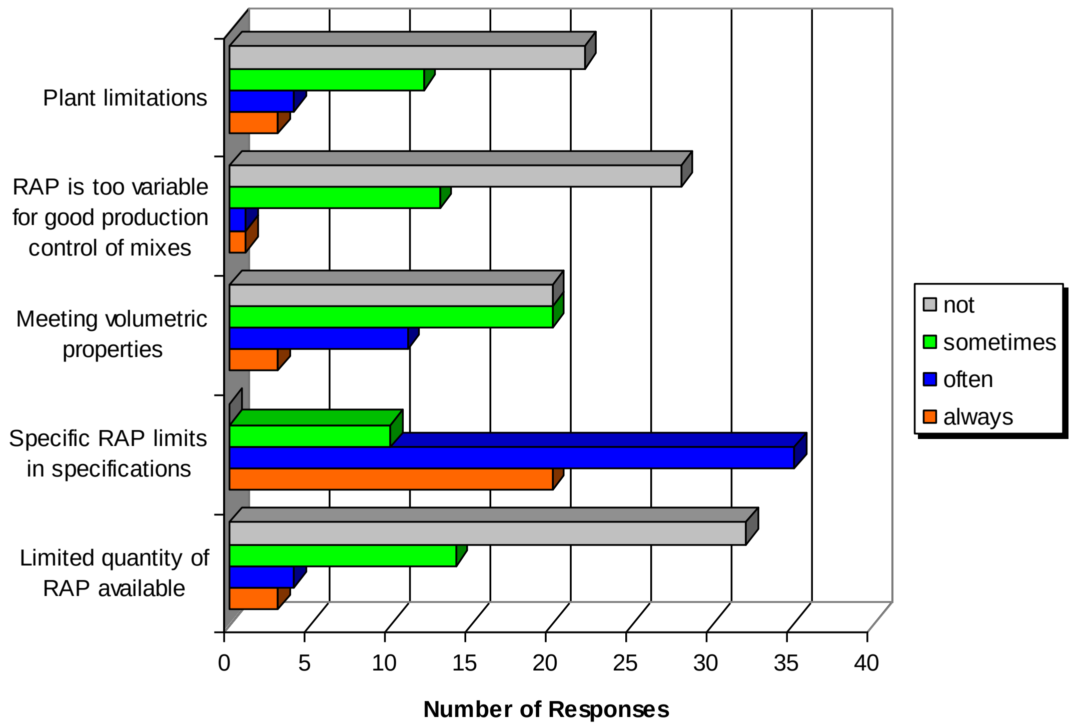

FIGURE 1. RESPONSES REGARDING FACTORS THAT LIMIT HIGHER RAP CONTENTS IN SURFACE MIXES. (WEST, 2008)

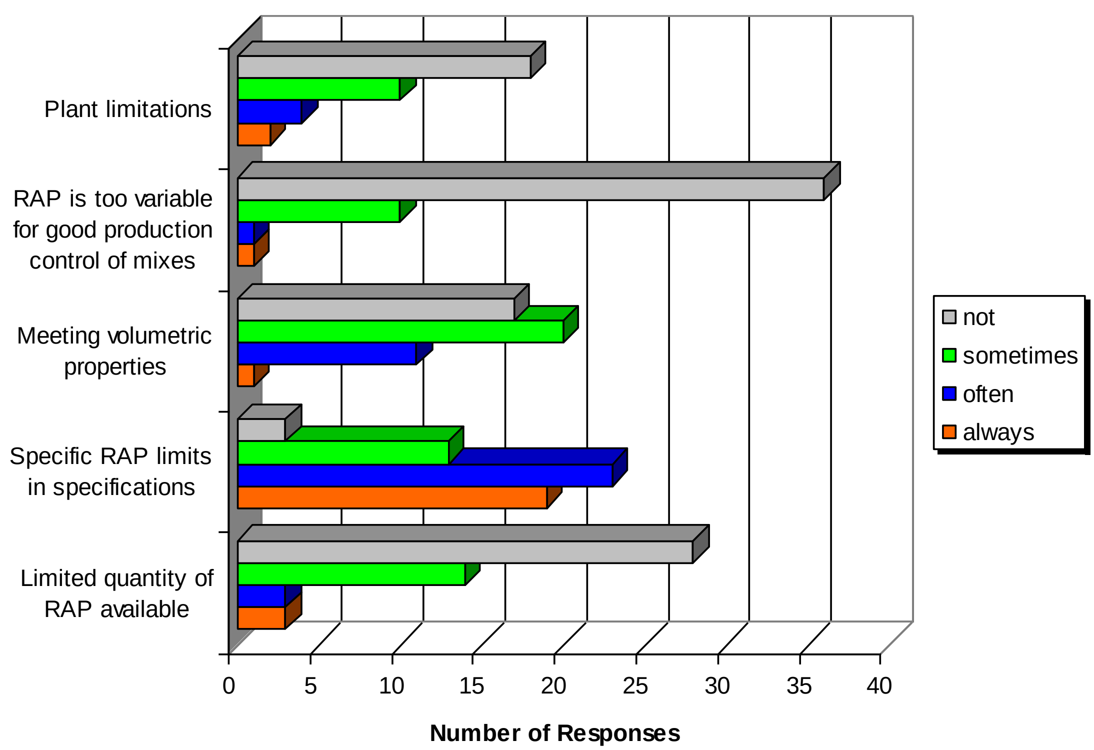

FIGURE 2. RESPONSES REGARDING FACTORS THAT LIMIT HIGHER RAP CONTENTS IN NON-SURFACE MIXES. (WEST, 2008)

2. RAP VARIABILITY

RAP material is obtained by milling the original pavement which sometimes contains patches, chip seal, and other maintenance treatments. Stockpiled RAP material may be from the base, the intermediate, and the surface courses or RAP from several projects may be mixed in a single stockpile. Also included in the stockpiles could be RAP from private works which is not built to the same original standard. This RAP variability is one of the main concerns a pavement engineer has when using RAP.

To ensure that all the properties of RAP samples taken from asphalt plants have low variability, standards must be set for stockpiling in the state of New Jersey. In order to do this, all stockpiling methods must be analyzed to determine which methods minimize variability. Research has already been conducted for the development of stockpiling procedures within the states of Indiana, Illinois, and Florida ((IowaDOT, 2006) (McDaniel & Anderson, 2001)). The US Department of Transportation also has set stockpiling procedures in an effort to minimize variability within aggregate stockpiles (USDOT, 2006).

It is important that RAP has minimal stockpile variability in order to quantify the effects that it will have on the virgin binder. Variation in stockpiles is determined through a variety of asphalt property tests such as moisture and asphalt content, maximum specific gravity, and viscosity. The grain size distribution of RAP stockpiles is also used to quantify their variability (Newcomb, 2007). As mentioned before, certain states have already attempted to limit the variability of stockpiles; however it is important to look at the climates of each of these states to see how they compare to New Jersey's climate.

In states that have harsh climates, stockpiling procedures will be significantly stricter. Detailed procedures are utilized to reduce the chances of negative weathering effects due to these climates. These negative weathering effects can have a significant impact on the variability of RAP stockpile. For example, states that receive a lot of precipitation are required to provide proper drainage for their stockpiles in order to prevent the segregation of aggregates and high moisture contents. In order to use standards set by other states in New Jersey, it is important to compare the climates to make sure they are harsher. Indiana and Iowa are states that have done intensive studies on RAP and have harsher climates than New Jersey; therefore, it is justifiable to use quality control procedures from Indianapolis and Iowa in order to set standards for stockpiling. Climate pattern data obtained from the National Oceanic and Atmospheric Administration (NOAA) shows that the climates of Indianapolis, Indiana; and Des Moines Iowa have harsher climates than Millville, New Jersey (NOAA, 2009).These climate comparisons can be found in Appendix A1. Florida, however, does not have a harsher climate than New Jersey, yet it would still be beneficial to research their findings on the variability of RAP stockpiles. DOT specifications for stockpiling practices were tabulated in Table 1.

TABLE 1. STATE SPECIFICATION FOR STOCKPILING IN DIFFERENT STATE

State	Percentage of RAP allowed	Stockpiling practice	Protection from moisture	Particle size Regulations	Sampling procedure
Iowa (IowaDOT, 2006)	Up to 20% RAP allowed 20-30% RAP – Binder grade decreased one step Greater than 30% - binder grade determined by testing performed by the Contracting Authority	Separate stockpile shall be for each source of RAP based on the quality of aggregate, type and quantity of asphalt binder, and size of processed material.	It shall be placed on base with adequate drainage.	Maximum particle size of 1.5 inch	At least from three location. Or minimum 50 ft of project length for each sample.
Indiana (INDOT, 2008)	20% - Surface 50% - Base	Each stockpile labeled with information on size of material and area where material was taken from Stockpile height can 't exceed 3 meters	No Tarps Under a roof, can be open building Stockpiles must not be low and spread out.	100% of RAP particles should pass 2 in sieve	ITM 207 – Sampling AASHTO T 248 – Sample Reduction Sample size dependent on nominal max particle size
Florida (FDOT, 1999)	60% Base 50% Binder	Stockpiles properly labeled with location where RAP were gathered from Stockpiles must be placed above water table	Cover RAP stockpiles when feasible (no tarps) Place RAP on a solid paved surface Stockpiles must not be low and spread out.	One stone size lower than the nominal max size of the aggregates used in the mix No soft particles, stockpile not a majority of fines	Cut 10, 6 inch cores from pavement being milled or remove 200 ft of milled asphalt at the full depth specified for pavement removal

Whenever higher amounts of RAP are used in the design, restrictions on stockpiles become more stringent. It is advised to separate the stockpile into two or more parts to minimize the variability. There are two types of stockpiles, separated and composite. In a separated stockpile, RAP is stored as per source of material i.e. RAP from different source stored separately. In a composite stockpile, RAP from different sources are combined together. The composite stockpiling method saves space, but should be employed whenever identical RAP products are available (Decker, 1997).

RAP has tendency to form "crust" due to solar thermal effect which protect RAP from external moisture. This layer is easily broken by front-end loader hence short stockpile are subject to larger moisture accumulation than tall and conical stockpile. It is not advisable to cover RAP with tarp or plastic as it causes condensation under this covering. Hence RAP is generally kept open or stored in open shade having paved ground. Paved ground contributes to drainage from RAP and reduces moisture adsorption from ground. Generally 7-8% of moisture in spring at low and horizontal stockpile is observed. Maintaining RAP stockpile is relatively economical for large production as it reduces fuel consumption and increase percentage of RAP used in HMA (Decker, 1997). As per the NCAT survey (West, 2008) (Figure 3) 53% responders do not employ any special stockpiling practice, 33% of responders place RAP stockpile in sloped surface to drain the moisture, 17% of responders place the RAP on paved surface to avoid contamination with underlying material, 9% of responders place the RAP under cover to minimize accumulation of precipitation.

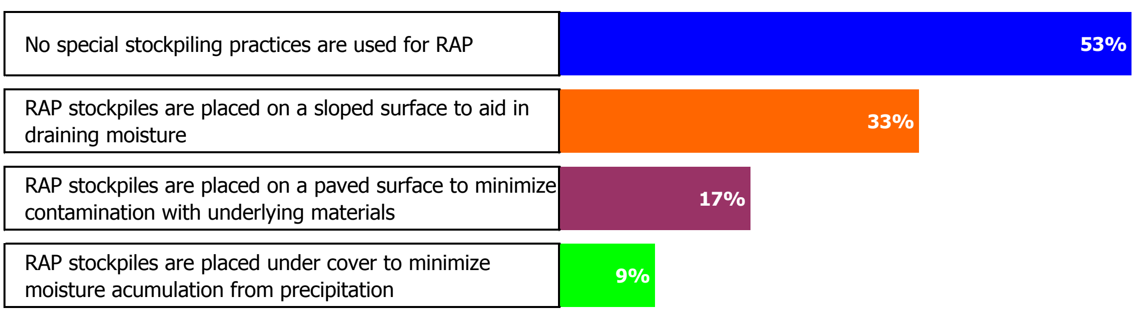

FIGURE 3. SUMMARY OF RAP STOCKPILING PRACTICES (WEST, 2008)

3. SAMPLING RAP

The sample used for testing is obtained from stockpiles, roadways, or haul trucks. These samples must represent the properties of entire stockpiles used for HMA design. RAP sampling is similar to aggregate sampling. When collecting RAP materials to be used in the mix design process, larger samples may be needed because Superpave specimens are much larger than Marshall or Hveem specimens. Each sample must be of sufficient size for extraction, recovery, and testing of asphalt binder. Each state has a specific sample size requirement; generally a sample of at least 25 kg (55lb) is needed to fulfill the Superpave mix design criteria (McDaniel & Anderson, 2001). When sampling a pile, it is important to sample from several locations to try to avoid taking the entire sample from a segregated area. Standard deviation of asphalt content must be in the range of 0.2 to 0.5. RAP stockpiles having higher standard deviation values will be more difficult to deal with during the construction process (Newcomb, 2007). As per the

NCAT survey (West, 2008) (Table 2) 43% responders carry out at least one test to determine RAP asphalt content and gradation per 500 tons or less RAP. Responders were also asked to input asphalt content, its standard deviation, median sieve size (sieve size closest to 50% passing of the extracted RAP aggregate) and 75 micron sieve. Results indicate (as shown in Table 3) that a stockpile generally had 5% asphalt content with 0.1 to 1.5% standard deviation, 52% pass median sieve and 8% pass the 75 micron sieve.

TABLE 2. FREQUENCY OF TESTING RAP ASPHALT CONTENT & GRADATION (WEST, 2008)

Testing Frequency (one test per…)	% of Responses
500 tons or less	43%
Greater than 500 tons, less than or equal to 1000 tons	33%
Greater than 1000 tons, less than or equal to 2000 tons	20%
Greater than 2000 tons	4%

TABLE 3. SUMMARY OF QC STATISTICS FOR RAP STOCKPILES.(WEST, 2008)

RAP property	Count n	Average (%)	Standard Deviation (%)	
			Average	Range
Asphalt Content	70	5.0	0.46	0.1 to 1.5
% Passing Median Sieve	58	51.7	4.32	0.78 to 9.0
% Passing 75 micron Sieve	58	7.37	1.09	0.3 to 3.0

A. ROADWAY SAMPLING

Many states use cores from existing roadways to measure the properties of the in-place pavement before recycling. Selection of the number of samples per unit length depends upon historical data such as construction plans, past condition surveys, and maintenance records. The pavement is to be separated into construction units of similar composition using historical records. Each construction unit should be divided into six to eight sections of equal length. One sample should be selected from each section shows sampling frequency and sample size for those state highway agencies that performed evaluation during the project development stage. A minimum of one sample (consisting of 3 cores) per 1.6 lane-km (1 lane-mile) is recommended. For a detailed sampling plan, see the flow chart shown in Figure 4 can be used for evaluating any significant difference in properties of the RAP material (Kandhal & Mallick, 1997).

TABLE 4. RAP SAMPLING FREQUENCY AND SIZE (PUBLICATION NO. FHWA-SA-95-060).

State	Sample Frequency	Sample Size
Arizona	3 cores/1.6 lane-km	150 mm diameter for the full depth of structure
Florida	1 set of 3 cores/1.6 lane-km. Minimum 2 sets of 3 cores per lane.	150 mm diameter for the full depth of structure
Kansas	3 Cores/1.6 lane-km Minimum 30 cores.	100 mm diameter for the full depth of structure
Nevada	1 core/750 lane-meter	100 mm diameter for the full depth of structure
Texas	10 cores/project	150 mm diameter for the full depth of structure
Wisconsin	1 core/800 meter	Surface area minimum of 230 cm2
Wyoming	2 cores/km	150 mm diameter for the full depth of structure

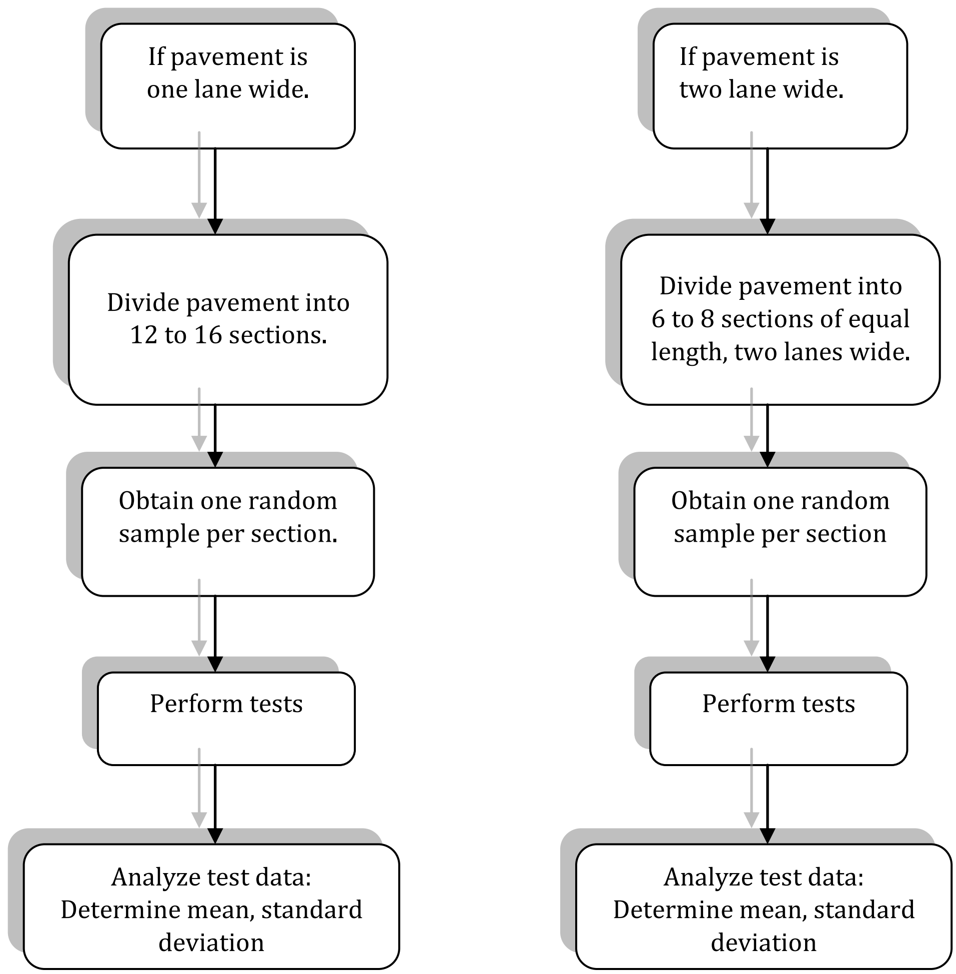

FIGURE 4. FLOW CHART FOR SAMPLING FROM PAVEMENT (KANDHAL & MALLICK, 1997)

B. STOCKPILE SAMPLING

The process of stockpiling may cause segregation of coarse material. To avoid this effect, at least 10 samples around the stockpile should be taken after removing 150 mm of material from the surface. Once the final sampling for the mix design is done no more RAP material is allowed to be added. Test result from stockpiles should be analyzed to identify any outlier. Material from the stockpile corresponding to the outlier should not be included in the mix design. Figure 5 shows process of sampling (Kandhal & Mallick, 1997).

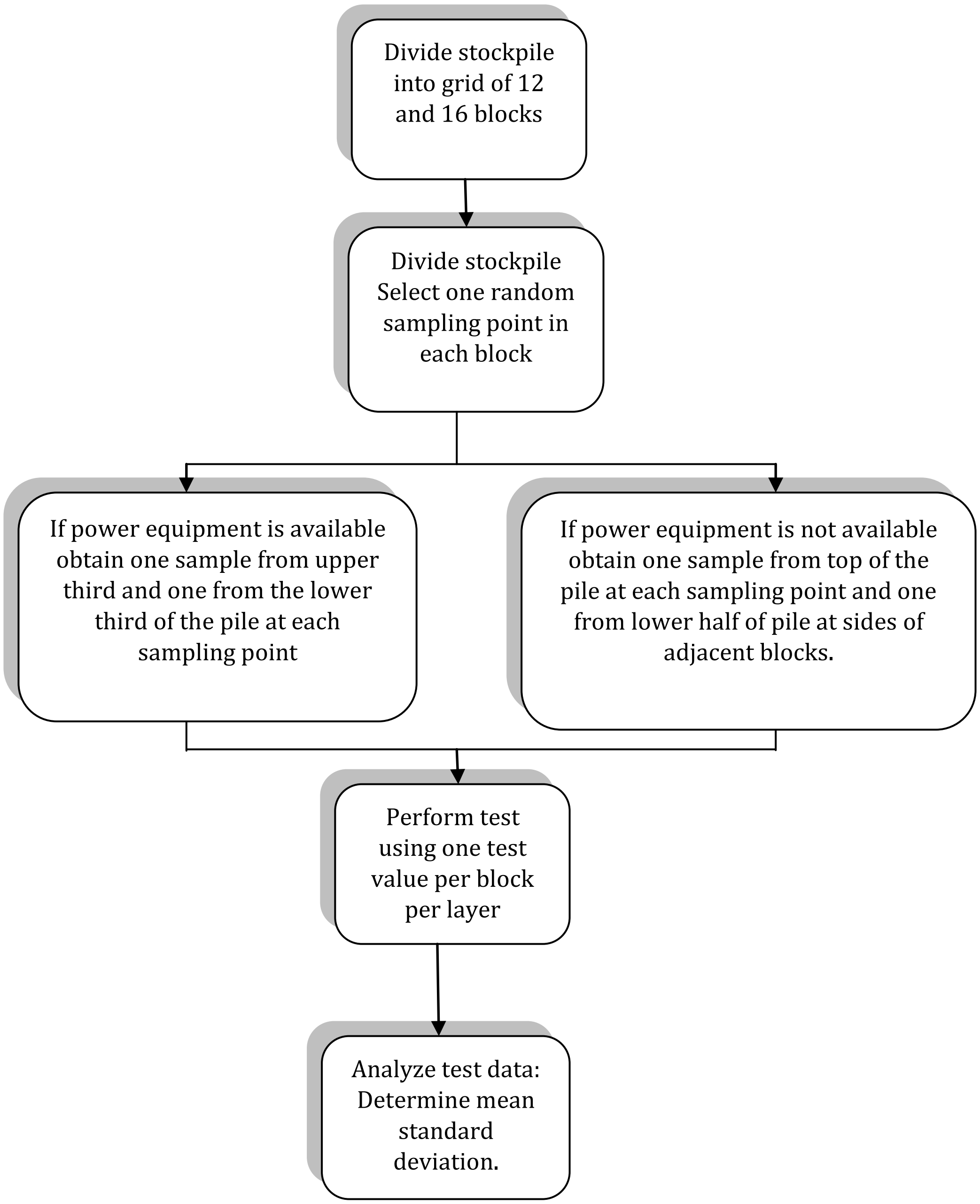

FIGURE 5. FLOW CHART FOR SAMPLING FROM RAP STOCKPILE (KANDHAL & MALLICK, 1997)

C. SAMPLE FROM HAUL TRUCK

RAP can be sampled from the trucks hauling milled material from the milling site to the plant location. AASHTO T2, sampling aggregates (pertaining to the sample from the hauling truck) can be used as guidance (Kandhal & Mallick, 1997). Figure 6 shows the flow chart for sampling from a RAP hauling truck. While sampling RAP from a truck, a trench with a level bottom is dug across the RAP. Samples should be collected at three locations that are spaced equally across the trench by digging in with a shovel (McDaniel & Anderson, 2001).

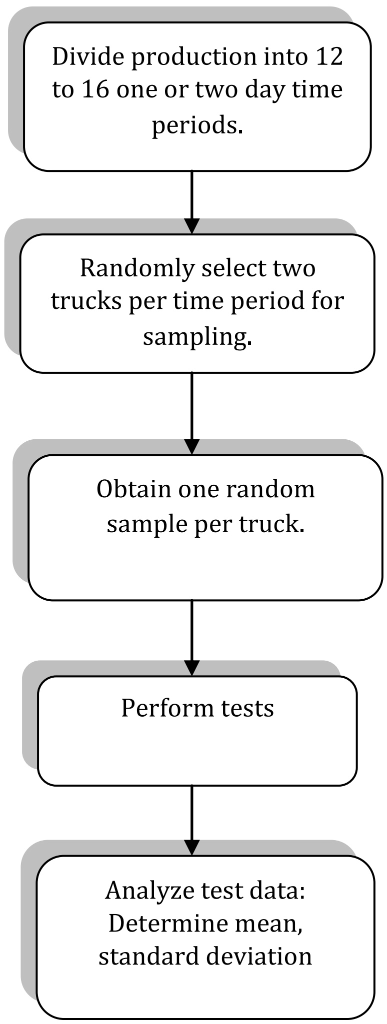

FIGURE 6. FLOW CHART FOR SAMPLING FROM RAP HAUL TRUCK (KANDHAL & MALLICK, 1997).

4. RAP AGGREGATE

McGennis (1995) has divided aggregate properties into two types, consensus properties and source properties. During the development of Superpave, pavement experts came to an agreement that certain aggregate characteristics were critical and needed to be achieved in all cases for pavement to perform well. Consensus properties are coarse aggregate angularity, fine aggregate angularity, flat, elongated particles, and clay content. In addition to the consensus aggregate properties, pavement experts believed that certain other aggregate characteristics like toughness, soundness, and amount of deleterious materials were critical; these were called source properties. FHWA Mixture Expert Task Group recommended to treat RAP as aggregate stockpile and does not recommended measurement of aggregate properties outlined by Superpave (Bukowski, 1997). RAP aggregates are obtained from milling of pavement; this process sometimes causes crushing of aggregate and increases the amount of fine aggregates and clay content. Beam and Maurer (1991) studied six RAP project and observed that gradation of RAP aggregate was finer than the core indicated.

Stroup-Gardiner and Wagner (1999) recommended fractionation of RAP into fine and course particle to reduce dust fraction in RAP mix and to allow higher percentage of RAP. NCHRP 9-12 and other DOT specification (IDOT, FDOT) has similar requirement regarding fractionation of RAP to reduce variability in final results due to non homogeneous stockpiling and agglomeration of RAP particles. As per the NCAT survey (West, 2008) (Figure 7) 74% responders crush all RAP into one sieve size. Also 52% responders use ½ inch sieve size which seems to be more popular among plant operators (Table 5).

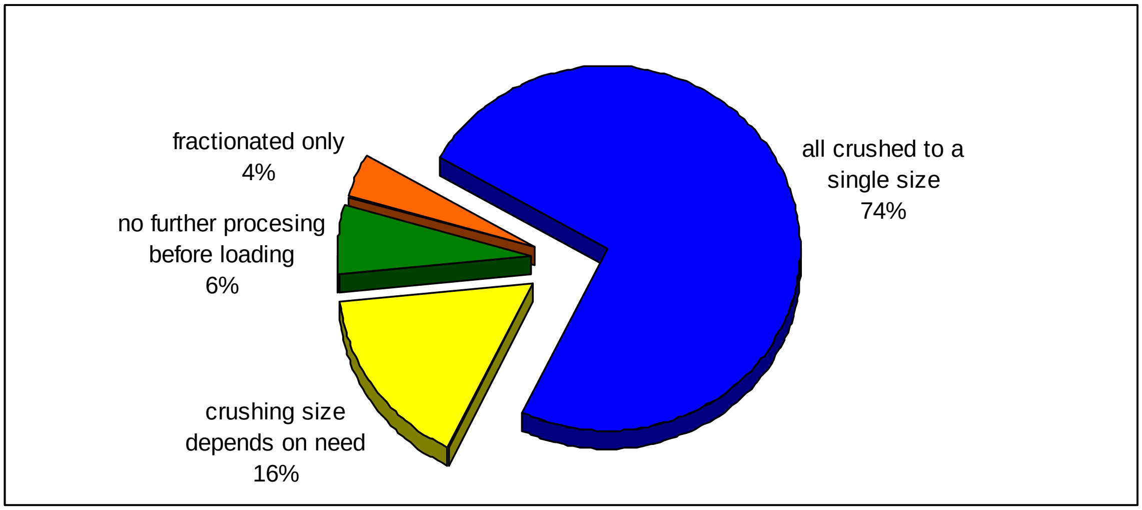

FIGURE 7. SUMMARY OF HOW RAP IS CRUSHED (WEST, 2008)

TABLE 5. SCREEN SIZES USED IN RAP CRUSHING (WEST, 2008)

Screen Size	% of Responses
< 1/2 inch	6%
1/2 inch	52%
5/8 inch	16%
3/4 inch	11%
1 inch	5%
> 1 inch	11%

Other concern regarding gradation of RAP aggregate is differential fine formation. RAP binder surrounding RAP aggregate consist of fines, whose dispersion in the mix depends upon the extent of blending. The blending phenomenon for high RAP is still largely unknown making quantification of these fines practically impossible hence making prediction of gradation impossible. Also when total bending doesn't occur, there is a layer of RAP binder surrounding the RAP aggregates which doesn't dissolve into the mix. This layer, known as the "mastic" layer, causes a change in gradation (Al Qadi I. L., 2009)

5. EXTRACTION AND RECOVERY OF RAP BINDER

When using high RAP in HMA, the allowable percentage of RAP and grade of virgin binder is dependent upon the characteristics and content of asphalt and the gradation and shape of the aggregate in RAP. These parameters are determined only after the binder and aggregate of RAP are separated. According to Zhang (1996) solvent extraction and the ignition oven method permits determination of binder content and aggregate gradation, both of which are required to design HMA while using high RAP. These methods are explained as follows.

A. SOLVENT EXTRACTION

BACKGROUND

It is necessary to use extraction and recovery procedures on reclaimed asphalt pavement in order to determine quality control, performance, and design parameters for hot mix asphalt. Through extraction and recovery procedures with solvent solutions, the binder is removed from the aggregates and is retrieved along with the aggregates for determination of properties. There are many characteristics of interest for the reclaimed binder such as aging, stiffness, and temperature susceptibility. The aggregate gradation of the RAP is important because ultimately the RAP will be used along with virgin materials to produce an asphalt mixture which will be used in a recycling project.

EXTRACTION PROCEDURES

There are many methods for the extraction of asphalt binder as outlined in ASTM and AASHTO standards. The general extraction methods from ASTM D2172-05/ AASHTO T 164-08 are the centrifuge extraction (Method A), reflux extraction (Methods B, C, D) and vacuum extraction (Method E) (ASTM, 2005) (AASHTO, 2008a). Methods A and B, the centrifuge and reflux methods respectively are the most popular among technicians and researchers. This is because of the simplicity of these test methods. The centrifuge and reflux are cold and hot solvent processes, respectively. A cold solvent extraction method is preferred over the hot solvent reflux methods because of the aging effects on asphalt binder that occurs from the high temperatures (Cipione, 1991). However there is the disadvantage that this method leaves up to 4 percent of asphalt binder on the reclaimed aggregate which is much higher than that of reflux extraction method. The binder that is extracted is still an accurate representation of the binder's properties (Stroup-Gardiner 2000, Peterson 1991).

However, there is another relatively new method for the extraction of asphalt binder as outlined in AASHTO T 319-08. This method uses an extraction vessel that was developed by Strategic Highway Research Program (SHRP). The uniqueness of the method is that the vessel is cylindrical in shape and contains baffles inside so that while the vessel is rotated horizontally, the solution and reclaimed asphalt cement inside mix more efficiently. The vessel is then placed vertically and the solvent and asphalt solution are extracted using vacuum. Inside the vessel there is a filtering system which consists of a series of different size mesh screens and metal spacers. The combination of spacers creates void spaces for the fines to collect and different size screens catch and remove unwanted particles from the solvent mixture. The binder and the solvent mixture that are extracted from the vessel are then transported into a flask where they will then be filtered through 20-µm retention filter catching the remaining amount of fines (AASHTO, 2008b). The advantage of this new extraction method allows for more complete extraction of the binder from the reclaimed aggregates, leaving approximately 1 percent (Peterson, 1999*)*. The one disadvantage of this method is the dissembling and cleaning of the vessel after each test sample is tedious and labor intensive. Table 6 summarizes different extraction methods.

TABLE 6. SUMMARY OF EXTRACTION METHODS

Extraction	**Method**	**Solvent**	**Advantage**	**Disadvantage**
Centrifuge	A	Cold	Simple test Widely practiced Can be used for binder properties	Leaves 4% binder
Reflux	B C D	Hot	Widely practiced	Aging effects from high temp Causes hardening of binder Leave too much binder Should not be used for binder properties
Vacuum	E	Cold	No aging from high temp	Not much in known
SHRP	-	Cold	Leaves 1% binder No aging from high temp Can be used for binder properties	Labor intensive test Costly (vessel machining/owner supply)

RECOVERY PROCEDURES

There are two methods used for the recovering of the asphalt binder from the extraction solvent. The first method is abson recovery method (ASTM D1856-95a(2003) and AASHTO T 170-00). This method has been used since the early 1930s and is effective in the removal of the majority of the solvent from the asphalt binder. As per previous research, this method leaves a considerable amount of residual solvent in the binder which creates a reduction in the binder's stiffness and also uses high temperatures which ages the binder (Peterson 1991, 10-11). The second method employs a rotary evaporator (ASTM D5404-03 and AASHTO T319-08). This method has several advantages over the Abson method which include a lower heat, mixing for a uniform binder consistency, simple and less labor intensive procedure. In this method, most of the residual solvent gets removed with the rotary action and lower heat causes less aging of the binder (Collins-Garcia 2000, Stroup-Gardiner 2000). Table 7 summarizes different recovery methods.

TABLE 7. SUMMARY OF RECOVERY METHODS

<table>
<tr><th>Recovery</th><th>Advantage</th><th>Disadvantage</th></tr>
<tr><td rowspan="4">Abson</td><td rowspan="2">Widely practiced (1930s)</td><td>Leaves residual solvent (lowers stiffness)</td></tr>
<tr><td>Skewed binder properties</td></tr>
<tr><td rowspan="2">Less Costly Procedure</td><td>High energy (ages binder)</td></tr>
<tr><td>Labor Intensive</td></tr>
<tr><td rowspan="4">Rotary Evaporator</td><td>Widely practiced (1970s)</td><td rowspan="4">Aging effects from high temp</td></tr>
<tr><td>Less heat (less aging of binder)</td></tr>
<tr><td>Mixes for a uniform binder consistency</td></tr>
<tr><td>Less labor intensive</td></tr>
</table>

SOLVENTS

There are several solvents that can be used in the extraction and recovery process. Each solvent has different properties related to its ability to dissolve asphalt binder and the quality of the asphalt you get after the process is completed. These solvents also have several safety and health concerns that also must be addressed for the well being of those performing the extraction and recovery.

The most widely accepted solvent for use is trichloroethylene, but there are a lot of concerns with this solvent. Trichloroethylene (TCE) had been identified as a carcinogen that is known to cause other health concerns such as headaches, dizziness, and tremors. Exposure at high levels has even been known to cause death. The possible alternative to this is EnSolv which has as its primary component n-propyl bromide. This alternative is not currently designated as a carcinogen. EnSolv has no recorded cases of death or respiratory ailments.

Tests were performed on both solvents to see if their properties are comparable. The difference in mean solubility between the two solvents varied by only 0.098 percent. With the exception of two of the asphalt samples tested, the difference between the solubility of the two solvents proved to be statistically insignificant. The tests were repeated for the anomalous samples and it was found that the difference between the two solvents was 0.013 percent for one and 0.105 percent for the other. Due to the small values for all practical purposes there was very little difference between solvents (Collins-Garcia and Roque, 2000).

The results for the extraction and recovery process showed that EnSolv and recovered EnSolv from the standpoint of extraction would be a suitable replacement for trichloroethylene. The EnSolv and recovered EnSolv were also shown to require less time to complete the recovery process than trichloroethylene. Viscosities of all recovered binders from both solvents were comparable. The overall results of the study show that EnSolv is a viable replacement for trichloroethylene (Burr and Davison, 1991).

B. IGNITION METHOD

In the ignition method, the change in mass of asphalt concrete is obtained after burning the RAP sample in oven at 538°C until the asphalt burned off. This process gives the RAP binder content. In this process, some aggregate mass also gets burned off which causes error in prediction of asphalt content. Brown and Mager (1996) carried out round robin study at NCAT to determine accuracy and precision of the method and found that ignition method can determine asphalt content of HMA with precision greater than extraction recovery method without significantly affecting gradation of aggregate. They also described the method of determining correction factor which was further developed by Zhang (1996) to determine combine correction factor for multiple source of aggregate. To account for the burning of aggregates, the correction factor is determined by placing an aggregate-only sample into the ignition oven and measuring the mass loss. Sondag et al. (2002) recommended keeping the 2000 gram of sample at 110°C for 40 min before ignition test to remove most of the moisture from the sample. Simplicity and accuracy of this method makes it popular among RAP plant operators. As per NCAT survey (West, 2008) (Figure 8) approximately 85% responders determine asphalt content using ignition method.

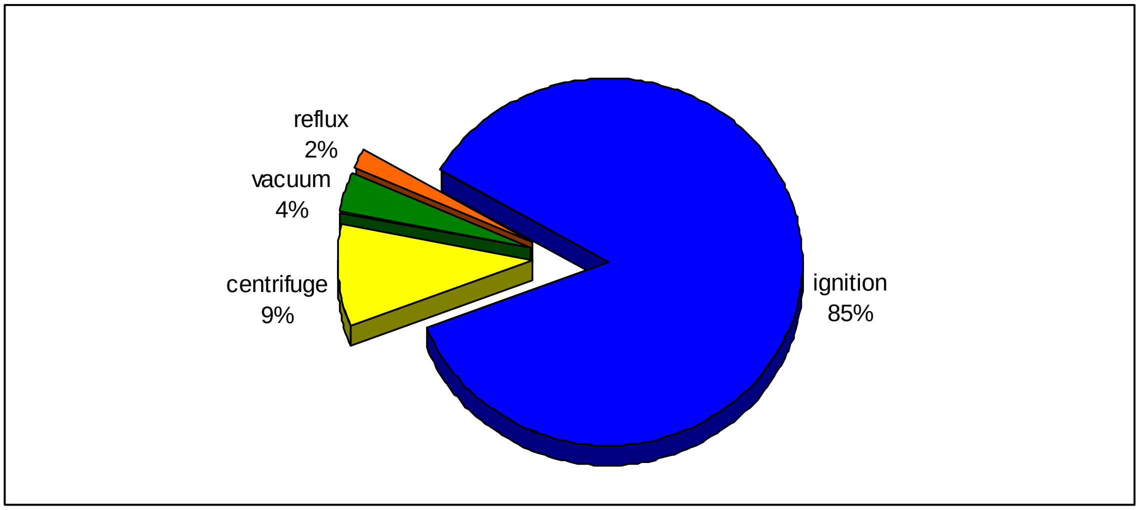

FIGURE 8. METHODS USED TO DETERMINING ASPHALT CONTENT OF RAP STOCKPILES (WEST, 2008)

The high RAP pilot study conducted by Rutgers University (Presentation by Thomas Bennert, Rutgers Asphalt Paving Conference, 2009) showed that the RAP binder in mix may not be fully mobilized. This effect combined with over predicting of asphalt content in RAP by 1.2% using Ignition Oven Method may lead to considerable under asphalting of RAP mixtures. To compensate for this problem, the Rutgers research team suggested designing Superpave mixtures at a lower gyration level than those determined from the traffic level. For example, they recommend to design a “H” level traffic mix at “M” gyration level. This will tend to increase the asphalt content. The beam fatigue data presented at the conference showed that the fatigue performance of 15% RAP with design AC at appropriate gyration level was similar to that of 24% RAP at lower gyration level or at increased asphalt content. Based on this study they have recommended increasing RAP to 24% and designing at a lower gyration level.

6. RAP BINDER PROPERTIES:

The recovered RAP binder sample is then tested to evaluate its rutting and fatigue performance properties. These properties are influence by RAP binder aging during its production and service life. Asphalt aging affects chemical, mechanical and rheological properties of asphalt binder. The following topics are discussed in detail about the binder aging and the tests performed to evaluate binder performance. Also included is discussion of the results of research work done on RAP binder.

A. Binder aging
B. Binder tests
C. Rejuvenation of RAP binder

A. BINDER AGING

Asphalt binder undergoes two types of aging: short term aging and long term aging. Short term aging is primarily due to volatilization, during heating process of HMA production. Long term aging is caused during service life of pavement and caused by oxidization. Aging of asphalt causes an increase in binder viscosity. This increase in viscosity causes increase in cracking failure and moisture susceptibility and decrease mixture wear resistance.

Asphalt is petroleum product made up of a variety of hydrocarbons with minor other components such as sulfur, nitrogen, oxygen and metals. The chemical composition of asphalt depends upon crude oil source and refining method. Asphalt binder consists of two chemical group asphaltene and maltene. These are made up of oils and resins. Resins are generally semisolids or solid in character. These resins are fluid when heated and brittle after cooling down. Oils are colorless white liquids. Resins act as agents to disperse the asphaltenes throughout the oil to provide a homogenous liquid (Petersen, 1984). (Corbett, 1975) has studied the process of aging and found out that as asphalt ages, maltene is transformed into asphaltene. This transformation leads to the increase in asphaltene content and decrease in maltenes content, which results in fewer maltenes available to disperse the asphaltenes. Presence of asphaltene causes flocculation without the presence of enough maltenes for dispersion, which leads to increased viscosity and decreased ductility which indicate poor pavement performance. Extent of aging is tested with standard tests like Rolling Thin Film Oven Test (RTFO) and Pressure Aging Vessel (PAV) and properties of binders are tested by using the Dynamic Shear Rheometer (DSR) and the Bending Beam Rheometer (BBR).

B. SUPERPAVE BINDER TESTS

Plant and field aging is evaluated by RTFO and PAV tests. The RTFO (ASTM D2872) simulates short term aging caused by in plant heating. The impact of short term aging on binder properties is used to compare rutting performance with those of new asphalt by conducting DSR, penetration and viscosity test.

The long term aging is simulated by PAV developed by Strategic Highway Research Program (SHRP). Residue from PAV is used to estimate the physical and chemical properties of an asphalt binder after 5 to 10 years in the field.

After conditioning asphalt binder through RTFO and PAV, rutting and fatigue performance is evaluated using DSR and Bending Beam Rheometer (BBR). DSR is used to compute complex shear modulus (G*) and phase angle (δ) at high and intermediate service temperatures. These two parameters represent asphalt binders resistance to shear deformation in the linear viscoelastic region. Complex modulus has two components: the storage modulus or elastic portion ($G' = G^*/\sin\delta$) which represents rutting performance and the loss modulus or viscous portion ($G'' = G^* \sin\delta$) which represent fatigue performance. As per PG specification, the storage modulus should be greater than or equal to 1 kPa and 2.2 kPa for original and RTFO asphalt binder, respectively. The fatigue parameter requires loss modulus to be a maximum of 5000 kPa for PAV aged binder.

BBR is used to determine low temperature thermal cracking performance of asphalt binder. In BBR, a simply supported prismatic beam of asphalt binder is subjected to constant load applied at its midpoint to calculate creep stiffness (S) and slope of master stiffness curve (m-value). As per PG specification creep stiffness should be maximum 300 MPa and m-value should be minimum 0.3.

C. REJUVENATION OF RAP BINDER

The above tests are carried out on the recovered RAP binder to determine the extent the RAP binder has been aged. The level of aging, or stiffness, indicates the amount of rejuvenating material required to add for better performance of the entire mix. Rejuvenating materials are generally types of oil that help RAP binder regain its mechanical and chemical properties, which are lost during the aging process. This rejuvenating material could be lower grade binder or rejuvenating agent which provide flux oil and lube stock to RAP mix. Some of the rejuvenators available in market are tabulated in Table 8.

TABLE 8. DETAIL OF REJUVENATOR AVAILABLE IN MARKET

Rejuvenators	Company	Unit Cost	Advantages	References
Black Night	Black Night	$9.94/gal	Increases traction; protects against chemical, oil, and gas spills; easy application; dries in 60 minutes; lasts 4 years.	(Black Knight Asphalt Rejuvenator)
Reclamite	RejuvTec	Waiting for reply	Lasts 4-6 years; stronger than most sealants (penetrates 3/8 of an inch); seals against intrusion of air and water; stops stripping of aggregates	(Rejuvtec)
TL-2000	Asphalt Institute	Waiting for reply	Dries in 60-90; increases tire grip 20%-30%; impervious to water; helps melt snow and ice; stays fresh in a closed container in open air for 2 years	(tl-2000 asphalt maintenance road coating)
AsPen	Sealmaster	$4.80/gal	Environmentally friendly; helps melt snow and ice; one coat application	(Maintaining the Worlds Pavements)
Asphalt Binder Plus	Sealmaster	$6.20/gal	Protects against cracks; recycling agent for RAP; environmentally friendly	(Maintaining the Worlds Pavements)
ARS	Lines and Signs Inc.	Waiting for reply	One coat application; increases traction and skid resistance; lasts 3-6 years; does not chip or peel	(Lines and Signs, INC)
Pass R	Western Emulsions Inc.	Waiting for reply	Made for RAP applications; forms a strong bond with old aggregate; protects from reflective cracking and moisture intrusion	(Western Emultions)

7. SUPERPAVE MIX DESIGN OF RAP MIX WITH LOWER GRADE VIRGIN BINDER

In 1997, Expert Task Group Guidelines were described by Bukowski, which were based on discussions with industry professionals. Though recommendations were not based on valid experimental results, the concepts behind the recommendations were sound. Bukowski (1997) suggested that general Superpave mix design requirements would remain the same for RAP mix and proposed a three-tier system which facilitated the selection of PG grade and percentage of virgin binder in RAP mix. The three-tier system is described as follows (Bukowski, 1997):

- Tier 1: Less than 15% RAP could be incorporated in mix design without any change in binder grade.
- Tier 2: 15% to 25% of RAP could be incorporated by lowering high and low grade of virgin binder by one grade
- Tier 3: To incorporate RAP higher than 25% blending chart could be used.

Kandhal and Foo (1997) at NCAT confirmed the use of the three tier system and also developed a "sweep blending chart" to determine the percentage of RAP if a three-tier system was not used. The "sweep blending chart" required determination of storage (G*/sin δ) and loss (G* sin δ) modulus for different percentage of virgin binder for high and intermediate temperatures. The percentage of RAP obtained by intermediate temperature sweep blending chart (average 37%) was higher than the typical average practice of around 15 – 20%. To rectify the discrepancy between calculated percentage of RAP and actual practice, Kandhal and Foo recommended a "specific grade" blending chart (Figure 9) which has reduced the effort of developing three sweep blending charts.

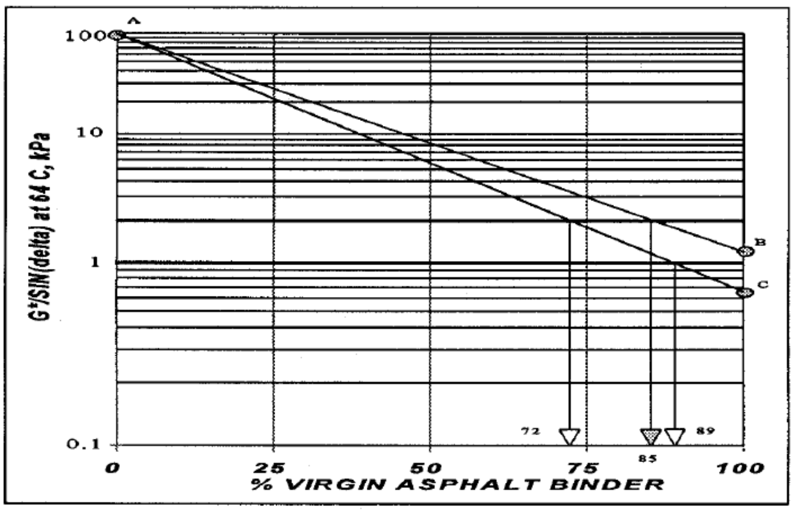

FIGURE 9. SPECIFIC GRADE BLENDING CHART (KANDHAL & FOO, 1997)

A "specific grade" blending chart is developed by plotting G*/sin δ values for virgin and RAP binder on log-log scale at required target high temperature grade. Consider an example given in Figure 9 where target high temperature is 64^{o}C and G* /sin δ of RAP binder is 100 KPa (Point A). For virgin binder, two binder grades, PG64-28 and PG 58-34 are considered whose G*/sin δ values are 1.13KPa (Point B) and 0.65 KPa (Point C). Two parallel stiffness lines for 1 KPa and 2 KPa gives maximum and minimum amount of virgin binder. From the plot, 85 to 100% of virgin binder (or 0 to 15% RAP) is required if PG64-28 binder is used and 72 to 89% of virgin binder (or 11 to 28% RAP) is required if PG58-34 is used. The study related to low temperature grade was not carried out by Kandhal and Foo (1997).

NCHRP 9-12 (McDaniel & Anderson, 2001) has recommended the use of the latest three-tier system (Table 9) which was modified to incorporate low temperature grade. The new three-tier system allows a maximum of 20% RAP without change in binder selection and up to 30% RAP by lowering one grade softer. The percentage of RAP decreases with an increase in low grade of virgin binder. For the use of high RAP design, a blending chart is recommended.

TABLE 9. SELECTION GUIDELINE FOR RAP MIXTURE (MCDANIEL & ANDERSON, 2001)

	RAP Percentage		
	Recovered RAP Grade		
Recommended Virgin Asphalt Binder Grade	**PG xx-22 or lower**	**PG xx-16**	**PG xx-10 or higher**
No change in binder selection	<20%	<15%	<10%
Select virgin binder one grade softer than normal (e.g., select a PG 58-28 if a PG 64-22 would normally be used)	20–30%	15–25%	10–15%
Follow recommendations from blending charts	>30%	>25%	>15%

Design of a blending chart is dependent upon the grade of virgin binder, percentage of RAP, and target PG grade. These variables can be fixed with the help of state specification or local availability of material. Blending charts can determine the PG grade of virgin binder if the target PG grade, the percentage of RAP, and the RAP binder properties are known or the percentage of RAP can be determined if the PG grade of virgin binder, the RAP binder properties, and the target PG grade are known.

Consider following two cases which illustrate use of blending chart.

Case 1: Determination of PG grade of virgin binder

To determine the high and the low grade of virgin binder, high, low, and intermediate critical temperature of RAP binder are required. These critical temperatures could be determined by BBR and DSR testing on the sample RAP binder. The critical temperature is the temperature at which storage modulus ($G^*/\sin \delta$), loss modulus ($G^* \sin \delta$), creep stiffness (S) and slope of master stiffness curve (m-value) for unaged (original), RTFO and PAV samples reach the critical values specified by the Superpave specification. Table 10 gives an example of critical temperature of recovered RAP binder.

TABLE 10. CRITICAL TEMPERATURE OF RECOVERED RAP BINDER (MCDANIEL & ANDERSON, 2001)

Aging	**Property**	**Critical Temperature, °C**	
Original	DSR $G^*/\sin \delta$	High	86.6
RTFO	DSR $G^*/\sin \delta$	High	88.7
PAV*	DSR $G^* \sin \delta$	Intermediate	30.5
		Low	-4.5
		Low	-1.7
	PG	Actual	PG 86-11
		MP1	PG 82-10
* Test RTFO-aged recovered RAP binder as if PAV-aged.			

Using a linear assumption with these critical temperatures, the percentage of RAP and target critical temperature straight line is drawn, which could be extended to find intercept on Y-axis to find critical temperature of virgin binder. Three blending charts for high, intermediate, and low temperature are developed. Figure 10 shows the blending chart for high temperature.

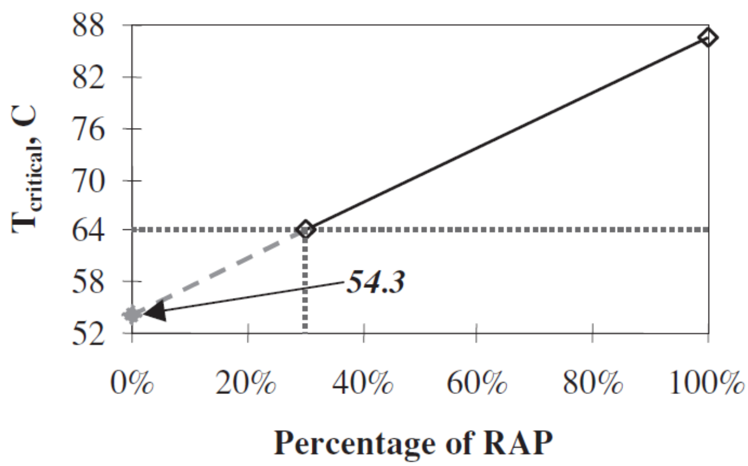

FIGURE 10. HIGH-TEMPERATURE BLENDING CHART FOR KNOWN RAP PERCENTAGE (MCDANIEL & ANDERSON, 2001)

Estimated critical temperature of virgin asphalt binder could be tabulated as shown in Table 11. In this example, a virgin binder with true grade of PG 54.3-26 is required to obtain a final blended binder PG grade of 64-xx. In practice, a virgin binder of PG 58-28 would be used which would result in a higher final blended binder grade.

TABLE 11. ESTIMATED CRITICAL TEMPERATURE OF ASPHALT BINDER (MCDANIEL & ANDERSON, 2001)

Aging	Property	Critical Temperature, °C	
Original	DSR $G^*/\sin\delta$	High	**54.3**
RTFO	DSR $G^*/\sin\delta$	High	53.4
PAV	DSR $G^*\sin\delta$ BBR S-value BBR m-value	Intermediate Low Low	**22.6** –15.2 **–16.4**
	PG	Actual MP1	PG 54-26 PG 58-28

Case 2: Determination of percentage of RAP

Procedure for designing of blending chart to determine the percentage of RAP is similar to Case 1. In this case, a straight line in the blending chart is drawn with known critical temperatures of virgin and RAP binder and percentage of RAP for target critical temperature is interpolated as shown in Figure 11.

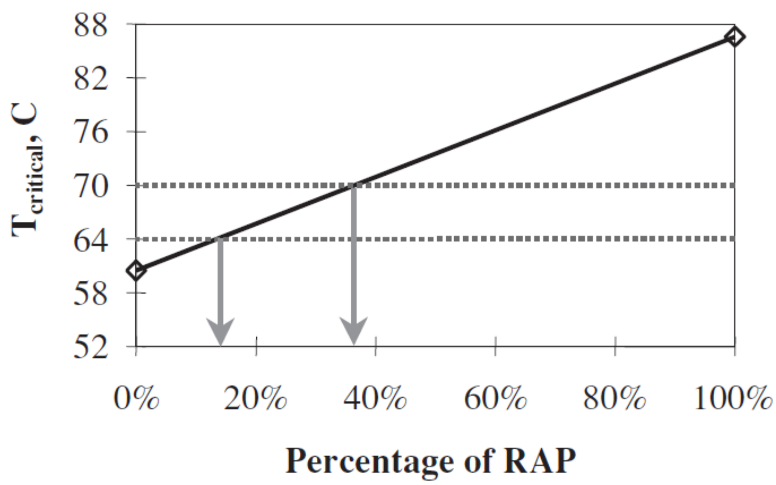

FIGURE 11. HIGH TEMPERATURE BLENDING CHART FOR UNKNOWN RAP PERCENTAGE (MCDANIEL & ANDERSON, 2001)

Asphalt binder is graded at 6^{o}C intervals, which gives a range of percentage of binder. Overlapping the range for high and low temperature is used. Blending charts for high and low temperature grade gives minimum and maximum percentage of RAP respectively. This should be lower than percentage of RAP obtained by intermediate blending chart.
Table 12 shows example of method of tabulation of estimated percentage of RAP to achieve final blending grade.

TABLE 12. ESTIMATED PERCENTAGE OF RAP TO ACHIEVE FINAL BLENDING GRADE (MCDANIEL & ANDERSON, 2001)

Aging	Property	Temperature	Percentage of RAP to Achieve PG 64-22	Percentage of RAP to Achieve PG 70-28
Original	DSR $G^*/\sin\delta$	High	**13.4%**	**36.4%**
RTFO	DSR $G^*/\sin\delta$	High	10.8%	32.5%
PAV	DSR $G^*\sin\delta$	Intermediate	**66.3%**	—
	BBR *S*-value	Low	57.6%	23.7%
	BBR *m*-value	Low	**40.5%**	**5.8%**

Once the percentage of RAP and virgin binder grade is known, the other Superpave mix design procedures remain the same. McDaniel and Anderson (2001) also recommended computation of bulk specific gravity by assuming percentage binder absorption of aggregate, deduction of RAP binder content from total asphalt content, and accounting weight of binder in RAP while batching aggregate.

Even though McDaniel and Anderson's (2001) recommendations are verified and accepted by most of the researchers, there have been efforts to simplify the procedure of mix design. Bautista et al. (2009) is carrying out the research at University of Wisconsin to eliminate complicated extraction-recovery method and to find out the low temperature rheological properties of RAP binder with a much simpler ignition method and a modified BBR test. Detailed investigation and testing is required to adopt this method in practice, its procedure explained as follows.

In this method stiffness of aged binder is determined by testing two types of binder samples and two types of mortar samples. The two types of binder samples tested are virgin binder in original state and virgin binder undergone two PAV cycles. The two types of mortar samples are fresh and artificial. Fresh mortar sample is prepared by mixing RAP aggregate and virgin binder in original state and artificial mortar is prepared by mixing Rap aggregate and virgin binder undergone two full PAV cycle to simulate aging of in service pavement. In both the mortar samples additional virgin binder (15% of RAP binder) is added. Relationship between binder and mortar stiffness is plotted to determine RAP binder stiffness. This RAP binder stiffness is used to plot blending chart of stiffness versus fresh binder content. Depending upon PG grade limit on stiffness percentage of RAP and virgin binder can be determined.

Al Qadi et al. (2009) are investigating double bumping (i.e. low and high grade softer than that of standard binder grade) of high RAP (40%) to reduce low temperature thermal cracking by comparing complex modulus and fracture energy. Use of softer binder has potential to reduce brittleness and premature cracking problems in HMA with high RAP. Complex modulus results indicate that high temperature bumping significantly affects the stiffness of mix, however effect of low temperature bumping is difficult to isolate by complex modulus test. Double bumping tested with semi circular bending (SCB) specimen at 0^0C and -12^0C, results indicate fracture energy of 40% RAP sample (1365 J/m^2) is higher than that of 20% RAP sample (1243 J/m^2) with standard binder grade (without bumping). Double bumping offsets the effect of RAP at intermediate temperature but at low temperature it is not that effective as viscoelastic nature of binder reduces below glassy transition temperature and the binder becomes brittle. More fracture energy tests are required to conclude requirement of double or single bumping at low temperature (-30^0C and -24^0C).

8. SUPERPAVE MIX DESIGN OF RAP MIX WITH REJUVENATING AGENT

Shen and Ohne (2002) had carried out a study to give a step-by-step procedure to determine the rejuvenator content in RAP mixture as per the Strategic Highway Research Program (SHRP) binder specifications. RAP content of mix containing rejuvenating agent is determine by adding ten percent to the percentage of RAP content specified by the three-tier system of McDaniel and Anderson (2001). To determine rejuvenator content, performance related properties like storage modulus (G*/sin δ), loss modulus (G*/sin δ), creep stiffness (S) and slope of master stiffness curve (m) for 0%, 5% and 10% rejuvenator are tested in DSR and BBR. Storage modulus is evaluated for original and RTFO sample at high temperatures, loss modulus is evaluated for PAV sample at intermediate temperature and stiffness and slope of master stiffness curve is evaluated for PAV sample at low temperature. High, intermediate and low temperatures of test are critical temperature of target mix. The graph of performance related properties and the percentage of rejuvenator are plotted by considering a linear relationship to extrapolate rejuvenator contents at critical values of performance related properties. Figure 12 shows a graph for storage modulus versus rejuvenator content at high temperature (64^{o}C) for original state. Rejuvenator content for original state whose performance related critical value is 1 KPa is 12.7%.

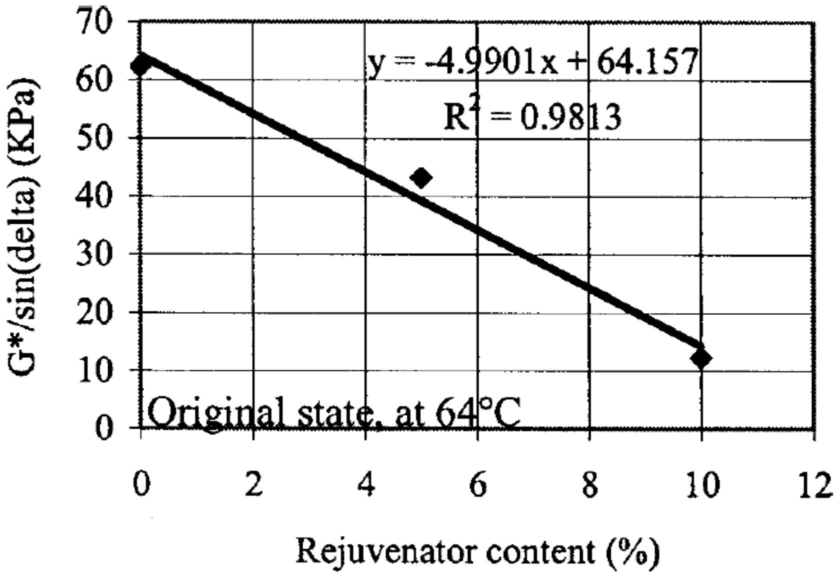

FIGURE 12. G* / SIN Δ VERSUS REJUVENATOR CONTENT AT 64°C (SHEN, AMIRKHANIAN, & MILLER, 2007)

Generally, the average of maximum rejuvenating content obtained at high temperature and minimum rejuvenating content obtained at intermediate and low temperature is taken. This rejuvenating content should be cross checked by referring manufacturer's recommendation. Nitrogen (N) to paraffin (P) ratio of rejuvenator should be higher than 0.5 to insure compatibility and to avoid hardening of binder. Rejuvenator should satisfy the ASTM requirement of viscosity, flash point, volatility, compatibility, chemical composition and specific gravity (Shen, Amirkhanian, & Miller, 2007).

PERFORMANCE OF RAP MIX WITH REJUVENATOR

State agencies put restriction on use of rejuvenator in HMA due to poor rutting performance and requirement of additional equipment (Shen, Amirkhanian, & Miller, 2007). Shen et al. (2007) tested the RAP mix (0%, 15%, 38%, and 48%) with and without rejuvenator. Indirect tensile strength and rut resistance of RAP sample with rejuvenator was found to be higher than that of without rejuvenator.

9. BLENDING OF RAP BINDER AND VIRGIN BINDER

The percentage of RAP, binder content or rejuvenating agent is determined by testing performance related properties of binder (Al Qadi I. L., 2009) (McDaniel & Anderson, 2001). Performance related properties of RAP mix or binder properties in the RAP mix depend upon the blending between RAP binder and virgin binder. Blending chart of RAP has been a critical research subject for long because this helps predict percentage of RAP and grade of virgin binder in RAP mix.

For conducting performance related tests four blending cases, black rock effect (BR), total blending (TB), partial blending (PB) and actual practice (AP) are compared. In black rock effect, it is assume that RAP binder does not contribute to the total binder content, and acts as an aggregate stockpile, whereas in total or partial blending case aged (stiff) binder is assumed to be contributed completely or partially. Overall gradation and total asphalt content of mix are kept constant for all blending cases to compare the effect of blending on volumetric properties and stiffness. If mix design is done by assuming BR effect but TB or PB effect occurs in the mix then total asphalt content and stiffness of mix will be more than expected.

To investigate blending phenomenon, Huang (2005) blended RAP with virgin aggregates without any new virgin asphalt binder being introduced. The mixture was mechanically blended (dry blended). The purpose was to find out the extent at which the aged asphalt from RAP particles would blend with virgin aggregate. Since the virgin aggregates were greater than No.4 size; and RAP particles were all screened by No.4 sieve, they were easily separable after the mixing. Irrespective of the RAP proportions varying from 10-30%, when blended at 190°C temperatures and mixed for 3 minutes, it was observed that the asphalt content of RAP reduced from 6.8 percent to 6.0 percent, which accounted for about 11 percent of binder loss due to pure mechanical blending. The results from pure mechanical blending indicated that aged asphalt tended to “stick” with the RAP aggregate. A very small portion (about 11%) of the aged binder was available to blend with virgin asphalt.

In order to determine how much virgin asphalt binder was “cut” into aged asphalt coating RAP aggregates, staged extraction was used. The Figure 13 below presents a schematic flow chart for the staged extraction which has been explicitly explained below the figure.

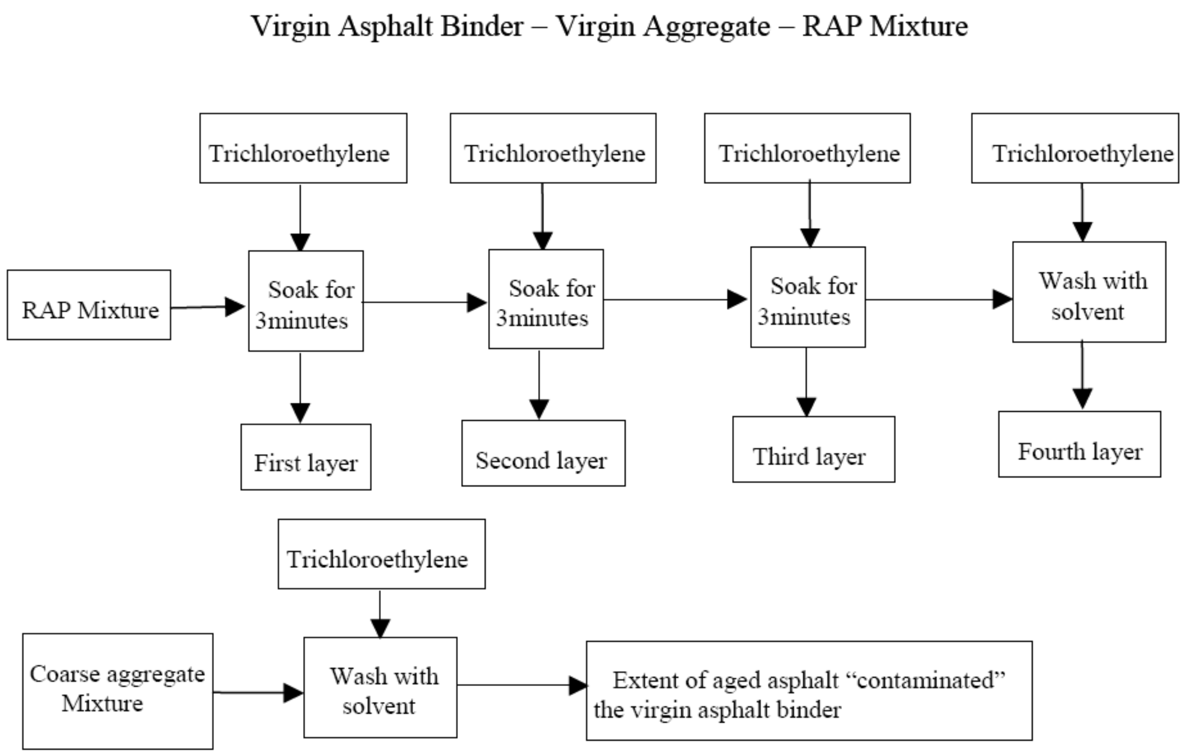

FIGURE 13. STAGED EXTRACTION- RECOVERY (HUANG 2005)

The RAP mixture was first soaked in trichloroethylene solution for 3 minutes, and the solution was decanted. This batch of extracted binder was considered as the 1st (outermost) layer of RAP particles. The same mixture was soaked into trichloroethylene again for 3 minutes to obtain the asphalt binder of the second layer, and so on. A total of four batches of staged extraction, representing four different layers of asphalt, were performed. The three minutes soaking time was determined through "trial and error" in order to produce similar amount of binder from each batches. The last batch was washed with solvent to remove all of the remaining asphalt binder. In addition, coarse (virgin) aggregate mixture was washed with trichloroethylene solution to determine the extent the aged asphalt "contaminated" the virgin asphalt binder.

Abson recovery was employed to recover the asphalt binder from the asphalt trichloroethylene solution. The recovered asphalt binder was subjected to rheological tests. The rheological properties of asphalt binders at different layers of RAP particles were calculated. It was clear that asphalt viscosity increased as it went from outside layers to the inside. Based on above staged extraction it is observed that about 60% of the total thickness (near to RAP aggregate) had asphalt properties close to pure RAP aged binder, whereas the outside 40% of the binders were blended with virgin binder.

Recently Al Qadi has carried out extensive research study at University of Illinois at Urbana-Champaign. To study the blending phenomenon complex modulus of two different RAP contents (20% and 40%) from two different sources were tested. In this study, RAP mix of AP samples were compared with sample simulating BR effect, TB effect and 50% blending. Results indicate that at low RAP content (20%) there was no difference in complex modulus for all four set of sample but for high RAP (40%) complex modulus of AP sample was higher than sample simulating BR, TB or 50% blending. These results confirmed the study carried out by McDaniel and Anderson (2001) who had studied blending of 10% and 40% RAP content and found that at low RAP content BR, TB, and AP case were statistically similar but at high RAP TB and AP were not different although both of them were different from BR case. In Al Qadi's study higher complex modulus of AP samples indicated higher stiffness, as per researchers this was due to selective absorption of lighter fractions in the aggregate surface over a time or due to change in gradation caused by partial blending (whose extent is unknown). Gradation change is cause either by formation of mastic layer or release of fine particles in RAP binder.

Also Environmental Scanning Electron Microscope Analysis (ESEM) was carried out to study the RAP particle mastic bonding and blending. Microstructure of HMA sample was investigated by taking different type of images like secondary electron (SE) and backscattered electron (BSE). In these images aggregate, air void and binder structure were differentiable but RAP and virgin binder were not differentiable. Hence alternate method was adopted in which titanium was added to virgin binder and SEM images and Energy Dispersive X-Ray spectroscopy scan was taken. This method was previously used by Lee et al (1983) which had shown micro scale interaction between virgin binder and RAP material. Detailed investigation of this method is under further study.

Al-Qadi et al. 2009 made three mixes consisting of 0%, 20% and 40% RAP. In all the three cases the overall gradation was kept the same. The Superpave mixture design of the above three mixes indicated that the binder content was same. The surface area of the aggregates was similar for all the three mixes due to similar gradations. Due to similar surface area and binder content of all three mixtures, it appears that 100% RAP binder was mobilized in all the three cases.

10. PERFORMANCE OF THE MIXTURES OF UNMODIFIED BINDER WITH RAP

A. LABORATORY PERFORMANCE

Various researchers have investigated the proper methods of utilizing RAP and the associated performance of HMA incorporating RAP. Results obtained have been widely scattered and no conclusion can be drawn from past research projects. The laboratory and the field performance of the RAP have been explicitly outlined below.

LABORATORY PERFORMANCE OF RAP MIXTURE AT HIGH TEMPERATURES

In the past, many researchers have evaluated the effect of RAP content in the controlled mixtures in the laboratory. Rutting being one of the major distresses in the pavement, the effect of RAP on the laboratory rutting performance has been evaluated by various researchers (Al-Qadi & L., 2007) (Huang, 2004) (G. W. Maupin, 2008) (West, 2008).

Researchers have observed that for the mixtures having similar binder content and binder grade, higher the content of RAP in the mixture, higher is the rutting resistance. The phenomenon discussed was observed when permanent deformation was evaluated by using the Asphalt Pavement Analyzer (Kim, Byron, Sholar, & Kim, 2007) (West, 2008) (McDaniel R. S., 2002) (Li, 2003) (Kennedy, Tam, & Solaimanian, 1998) (Soupharath, 1998) (Sargious & Mushule, 1991) (Huang, 2004), using Superpave Shear Tester to evaluate repeated shear constant height (McDaniel & Anderson, 2001) and the complex shear modulus (Al-Qadi & L., 2007). According to Roque (2002) and Villers (2004), the phenomenon of higher rutting resistance is due to the lower content of virgin binder in the RAP mix. On the other hand, when rutting tests were performed using APA (G. W. Maupin, 2008), it was observed that on an average there was no significant difference in rutting between mixtures with high (> 20%) and the low (<=20%) usage of RAP. The above phenomenon may be because of high variability of results on field core samples.

LABORATORY PERFORMANCE OF RAP MIXTURE AT INTERMEDIATE AND LOW TEMPERATURES

According to most of the researchers, fatigue is the critical distress observed when high percentage of RAP is used in the mixture (Lee, Soupharath, Shukla, Franco, & Manning, 1999) (Al-Qadi & L., 2007) (Kim, Byron, Sholar, & Kim, 2007). Though no significant trend was observed by all the researchers, the discrepancies amongst all the researchers are outlined below.

When tests were performed using the Superpave Shear Tester (Al-Qadi & L., 2007), and the indirect tensile strength (Kim, Byron, Sholar, & Kim, 2007) it was observed that as the percentage of RAP increased from 0% to 45%, the fatigue life decreased. (Lee, Soupharath, Shukla, Franco, & Manning, 1999) Testing conducted for the NCHRP 9-12 study also confirmed that when RAP content was greater than 20% lower fatigue life was observed (McDaniel R. S., 2002). On the other hand, it was discovered that as the RAP content increased from 0% to 30% its fatigue life was improved, when tested with indirect tensile strength test, semi-circular bending test and the four-point beam fatigue test (Huang, 2004) (Sargious & Mushule, 1991). Al-Qadi (2007) commented that the results for fatigue cracking is very unpredictable for higher percentage of RAP. The fatigue life measured using the constant strain testing method increased with the increase in RAP percentage however no consistent level of increase in the fatigue life is observed. Moreover, when beam fatigue tests were performed at different strain limits; (low, high and intermediate strain levels) no significant difference between average test result values for high (30%RAP) and control (0% RAP) samples was observed. (G. W. Maupin, 2008).

From the above observations, it is not certain that the fatigue life always decreases with the increase in the RAP content. But, if that is the case, McDaniel (2002) suggested decreasing the virgin binder grade to reduce the stiffness at higher percentage of RAP.

Based on numerous laboratory studies, mixtures containing RAP exhibited significant increase in stiffness and even improved fatigue resistance (Huang, 2004) (Sargious & Mushule, 1991). According to Huang (2005), the RAP modified asphalt mix is a particulate-filled composite material. Based on Eshelby's equivalent medium theorem, this type of composite materials can be assumed as a virgin asphalt mastic layer coating a "black rock" aggregates. The "black rock" aggregate is a two phase composite body with an aggregate particle coated with an aged asphalt mastic film. A composite analysis by Li, G., Zhao (2000) indicated that the aged asphalt mastic layer was actually serving as a cushion layer between the hard aggregate and the soft asphalt mastic. Therefore, the stiffness changed more gradually between the virgin binder and the aggregate causing the stress and strain concentration between the different components to be lower. It was concluded that the layered system in RAP helped to lower the stress concentration of HMA mixtures. Huang (2004) and Sargious & Mushule (1991) suggested that if the RAP acted as a “black rock” the stress concentration would be lower and the strength would eventually be higher.

MOISTURE SUSCEPTIBILITY

The percent of tensile strength ratio (%TSR) is defined as the Indirect Tensile Strength in wet state divided by that in the dry state. As per Superpave specification it should be higher than 80% but some states have different specification as per its weather condition like South Carolina Department of Transportation (SCDOT) has 85%.

Moisture resistance of mixture increases with increase in RAP content but when tested for Tensile Strength Ratio, results shows that tensile strength ratio increases from 0%-20% RAP and decreases from 20% to 40% RAP.(Al-Qadi 2007). According to Al-Qadi (2007) improved moisture resistance of RAP may be due to selective absorption of binder into aggregate that produces bond and helps in resisting stripping and possibility of incomplete blending of binders and formed double coating around the RAP aggregate. On the contrary, when Sondag et al (2002) evaluated TSR for 18 mixtures he found that all mixture had TSR more than 95% but no exact relationship between RAP content or grade of binder and TSR was found. According to him, addition of the RAP to the mixture had no positive or negative influence on the moisture susceptibility. Even Maupin (2009) found that there was no significant relation between the average TSR results and RAP when it used from 0-30%. Laboratory test was performed on cores collected from the field. This could be one of the reasons for not getting consistent results. However, TSR ratio of mixtures containing rejuvenator was lower than that of mixture containing lower virgin binder. Also there was no visual sign of stripping seen even for highest percentage of RAP (40%, 48%) for two different source of aggregate (Shen 2006). When Xiao (2006) estimated TSR of hot mix asphalt with varying rubber content (0, 5, 10, 15) % and 25 % RAP, he observed that all samples satisfied Superpave specification for SCDOT (TSR=85%) except for the mixture containing 15% of rubber.

B. FIELD PERFORMANCE

The virgin and 10-25 percent RAP mixture were made using the similar aggregates (type and gradation), that were produced by the same plant and were placed by the same contractor, and were subjected to the similar traffic and environmental conditions (Kandhal, Rao, Watson, & Young, 1995) It was observed that both virgin and RAP mix sections behaved similarly and there was no significant rutting and fatigue in the RAP mix sections. This performance was tested after one to two and a half years of service life (Kandhal, Rao, Watson, & Young, 1995). On the other hand, when Kandhal (1995) in his subsequent analysis compared 10-45 % of RAP mixture with the virgin mixtures, where the monitoring period was from one to three and a half years, there was no significant overall difference in the performance of virgin and RAP mix sections. He believed that one to three and a half years is not long enough to make a definitive evaluation of field performance of virgin and RAP mix sections. West (2008) also conducted a field performance test on the NCAT test track under heavy loading. It showed good rutting performance except for one of the section which included 20 percent of RAP and lower PG virgin binder. It was predicted that this phenomenon was observed when less stiff virgin binder was used with less percentage of RAP. It was believed that the 20% RAP section was more susceptible to rutting when compared with higher percentage of RAP sections because the RAP percentage was low and the aged binder in the mix was less. It was even observed that only two of the eighteen sections had shown longitudinal cracking. This was observed due to the impression left due to the previous distress in the section.

11. PERFORMANCE OF THE MIXTURES OF MODIFIED BINDER WITH RAP

A. LABORATORY PERFORMANCE

As discussed in the previous section, the use of high percentage of RAP in the mixture improves the rutting resistance and reduces the fatigue life. There were various studies conducted to improve the overall performance of the mixture by modifying the mixture (Kim S 2009) (Mohammad L N 2003) (West 2007) (Xiao 2005) (Huang 2004). This modification was done by adding materials such as polymer (SBS), rubber and sasobit. The effects of these modifications are discussed below.

LABORATORY PERFORMANCE AT HIGHER TEMPERATURES

When Kim (2009) performed the rutting test using Asphalt Pavement Analyzer using up to 35% RAP and 3% of SBS(Styrene Butadiene Styrene). He observed no significant difference in the rut depth of the mixture with the increase in the RAP content. On the contrary, when sasobit was added in 45% RAP mixture, the rut depth decreases as compared to 45% RAP mixture controlled sample (without sasobit) (West 2009). When rubber was added in the mixture, the rut depth decreased with the increase in the RAP content (Xiao 2005). However the decrease in the rut depth depends upon the size of the rubber, the type of the rubber and the quality of the aggregates. But for all the different combinations used by Xiao (2005) a decrease in the rut depth was observed.

LABORATORY PERFORMANCE AT LOWER AND INTERMEDIATE TEMPERATURES

SBS modifiers have become increasingly popular because of their ability to mitigate cracking (McDaniel 2003) (Corte 1994) (Roque 2004) (Waston 2003) (Von Quintus 2007) (Kim 2003). The addition of the polymers and rubber both increases in the cracking performance (Kim S 2009) (Xiao 2005) (Huang 2004). According to Huang (2004) the increase in the fatigue life trend is seen for RAP content up to 30%. The above phenomena must be due to the increase in the elasticity of the mixture by adding polymers. For higher content of RAP, the fatigue resistance is varied and the results obtained are inconsistent (Huang 2004).

12. SUMMARY

Use of RAP in HMA production is a cost effective and environmental friendly method of recycling without sacrificing pavement performance. As per most of the researchers and plant operators there is merit in increasing the maximum limit of RAP allowed in surface and base coarses in state specifications.

One of the reasons behind limiting higher percentages of reclaimed asphalt pavement content is the variability of the recycled material. RAP material is obtained by milling the original pavement. RAP may contain material other than asphalt and aggregate which may contaminate the RAP mix. Plant operators are aware of the problem with foreign material in mixes and have put good measures in place to ensure it stays out of the RAP. Also stockpiles of RAP often contain RAP from different projects having different job mix formulas (JMF).

Variability of RAP can be minimized and a quality product can be ensured by employing good stockpiling practices. Implementing good stockpile management and tightening QC/QA of the processed product will provide a more consistent product. Availability of a consistent product will increase the probability of using higher percentages of RAP in mixes. To appropriately quantify the variability, a RAP sample obtained for testing must represent the entire stockpile and it should be large enough to carry out all required testing. RAP sampling procedures are similar to aggregate sampling.

Generally, RAP aggregate represent approximately 95% of the RAP and the remaining 5% consists of asphalt binder. As said before, RAP is obtained by milling old pavement. RAP aggregate are assumed to satisfy all Superpave criteria and measurement of aggregate properties are not recommended. To reduce the variability of RAP, it is recommended to fractionate RAP into fine and coarse parts, which is very difficult to execute practically.

For high RAP mixes (greater than 30%) it is essential to know the RAP binder properties which determine the percentage of RAP and/or virgin binder grade. Solvent extraction of the RAP binder is used when binder properties must be determined. The extracted binder is then recovered for testing using the rotary evaporator method. It is the most critical step in the design of a high RAP mix. For determination of binder content and gradation of RAP a comparatively simpler ignition method can be used. Due to its simplicity it is more popular among plant operators and lab technicians.

DSR and BBR tests were carried out on extracted RAP binder to determine its rutting and fatigue performance properties. These performance properties changed for each stockpile depending upon the extent of aging it had undergone. Aging of RAP binder changes mechanical and chemical properties of RAP, the effect of which can be minimized by using a lower virgin binder grade or a rejuvenating agent. Percentage of RAP, virgin binder grade and rejuvenating agent are determined using blending charts in high RAP mixes. The blending charts are developed by considering a linear relationship between percentage of RAP (or percentage of virgin asphalt) and performance properties (storage modulus, loss modulus). The current method of determination of RAP content and the virgin binder grade is very complex and time consuming. Researchers are investigating simpler procedures which can be carried out in the plant by consuming less time and effort, such as developing a modified BBR method.

Research related to the amount of blending between RAP and virgin binder is inconclusive; still the assumption of 100% RAP binder mobilization is accepted by most of the researchers. Understanding of blending phenomenon will help in the understanding of RAP mix properties; hence investigation of blending phenomenon will be an issue for further study.

The findings from the detailed literature review demonstrated that the laboratory and the field performance of mixtures with high RAP are not consistent between studies. For example, some researchers have observed fatigue life increase, while others have found that fatigue life decreases as percentage of RAP increases. This inconsistency between results, demonstrates that the performance of HMA with high RAP is not clearly understood. There is a need to conduct an in-depth evaluation of high RAP mixtures utilizing locally available materials.

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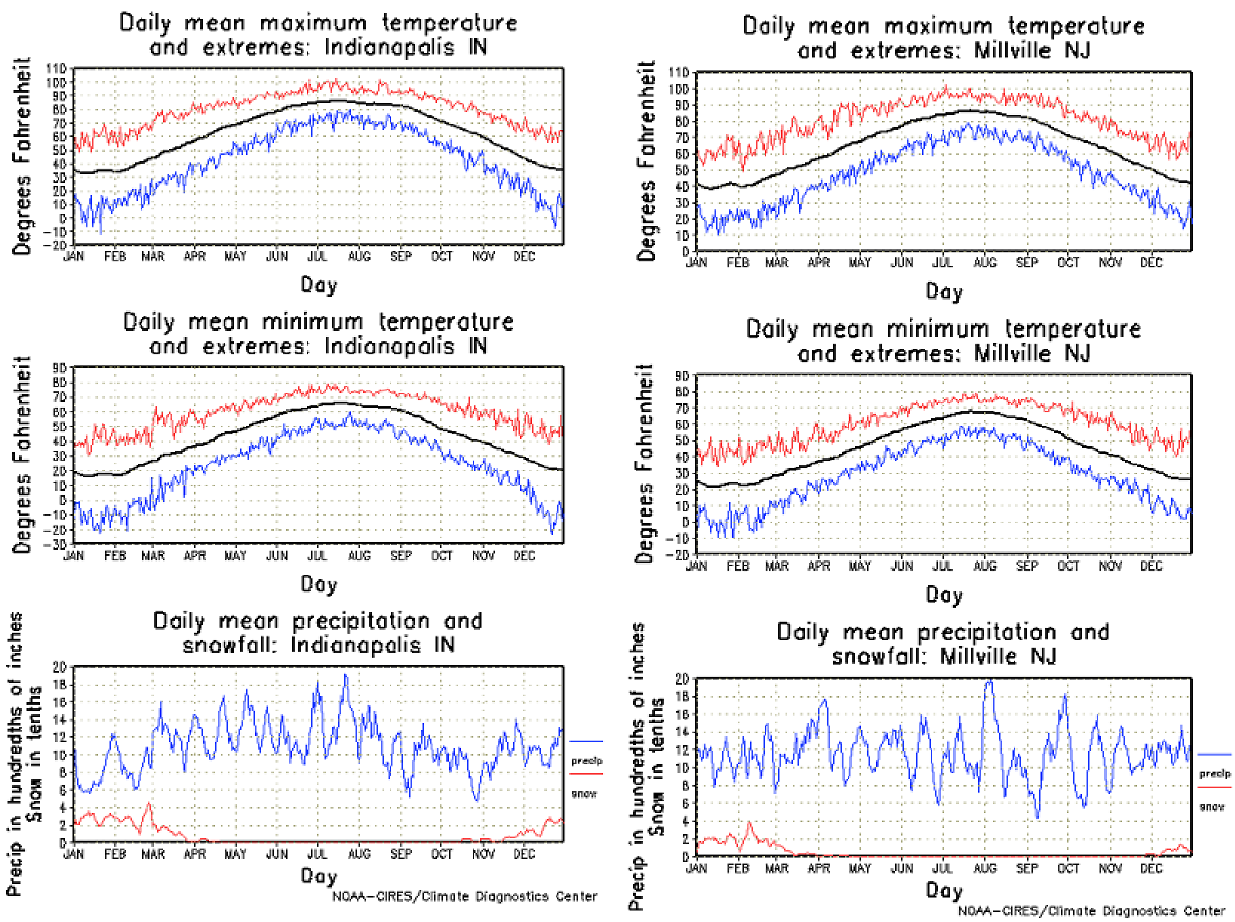


Climatology of Indana IN
Lat=39.4N Lon=86.2W Elevation=8.07 feet
Number of years available from 1961 to 1990: 30

Maximum temperature 1961 to 1990: 103 F
Minimum temperature 1961 to 1990: -23 F

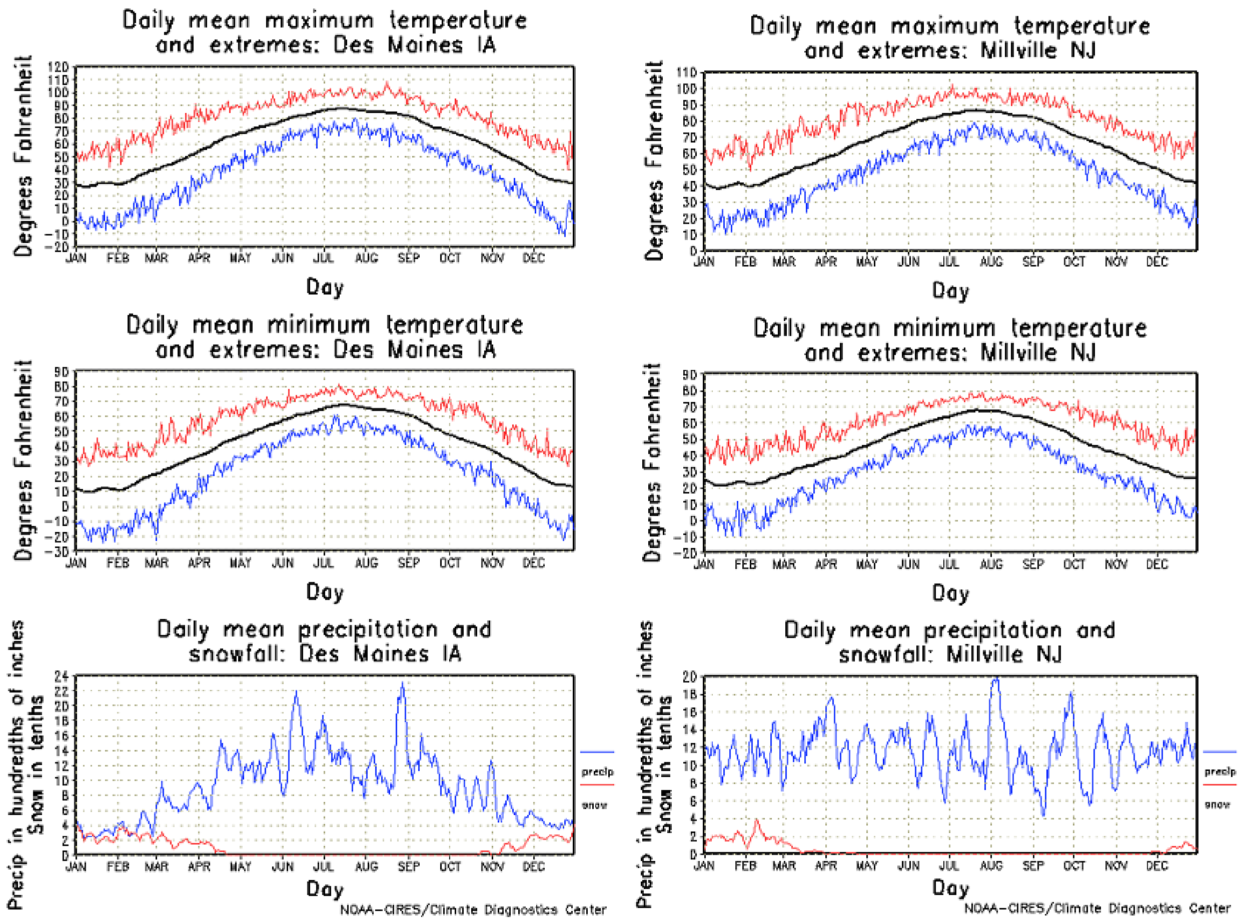
Mean Annual Precipitation: 39.9 inches
Mean Annual Snowfall: 27.5 inches

Climatology for Millville NJ
Lat=39.2N Lon=75.0W Elevation=72 feet
Number of years available from 1961 to 1990: 28

Maximum temperature 1961 to 1990: 102 F
Minimum temperature 1961 to 1990: -10 F

Mean Annual Precipitation: 42.1 inches
Mean Annual Snowfall: 15.3 inches

FIGURE 14. CLIMATE COMPARISON OF MILLVILLE NJ, AND INDIANAPOLIS IN



Climatology for Des Moines IA
Lat=41.3N Lon=93.4W Elevation=963 feet
Number of years available from 1961 to 1990: 30

Maximum temperature 1961 to 1990: 108 F
Minimum temperature 1961 to 1990: -24 F

Mean Annual Precipitation: 33.1 inches
Mean Annual Snowfall: 34.8 inches

Climatology for Millville NJ
Lat=39.2N Lon=75.0W Elevation=72 feet
Number of years available from 1961 to 1990: 28

Maximum temperature 1961 to 1990: 102 F
Minimum temperature 1961 to 1990: -10 F

Mean Annual Precipitation: 42.1 inches
Mean Annual Snowfall: 15.3 inches

FIGURE 15. CLIMATE COMPARISON OF MILLVILLE, NJ AND DES MOINES, IA

LITERATURE REVIEW OF SIMPLE PLANT TESTS

Consistent quality of asphalt concrete mix from the asphalt plant will help in constructing durable pavements. This can be achieved by testing the asphalt mix at the plant lab. Following are some of the tests which can be carried out at plant.

1. FLOW TIME TEST

The flow time test is a variation of the simple compressive creep test. In the creep test a static load is applied to a specimen and the resulting strains are recorded as a function of time. The variation introduced by the National Cooperative Highway Research Program (NCHRP) Project 9-19 is the flow time test. Flow time is defined as the time when the minimum rate of change in strain occurs during the creep test. It is determined by differentiation of the strain versus time curve (Bonaquist & Christensen, 2003).

In NCHRP Project 9-19, the flow time correlated well with the rutting resistance of mixtures used in experimental sections at MNRoad, WesTrack, and the FHWA Pavement Testing Facility. For tests at a given temperature, axial stress, and confining stress, the rutting resistance of the mixture increases as the flow time increases (Bonaquist & Christensen, 2003).

2. CREEP AND RECOVERY TEST

A creep and recovery test can be conducted in unconfined uniaxial compression. Table 13 compares the setup for the dynamic modulus test and the proposed creep and recovery test. The properties measured from these tests can be interconverted within the linear viscoelastic region.

TABLE 13. SIMILARITIES BETWEEN THE DYNAMIC MODULUS TEST AND THE CREEP AND RECOVERY TEST.

	Dynamic Modulus Test	**Creep and Recovery Test**	**Comments**
Property Measured	Dynamic Modulus, Phase Angle	Shape of Creep Compliance curve	The Creep Compliance and compliance slope is theoretically related to the dynamic modulus and phase angle.
Load Application	Dynamic	Static	Static methods are preferred for acceptable quality control testing. Dynamic methods have shown poor consistency when used in the field.
Frequency or Loading Times	25, 10, 5, 1.0, 0.5, and 0.1 Hz	Loading time(s) to be determined	
Load Control	Hydraulic	*Hydraulic	Tests that require hydraulically applied loads are used for many asphalt concrete property tests, including the dynamic modulus test. However, these types of tests are difficult to perform effectively in the field. A screw or weight type of load application is simpler and measured properties can be correlated with those of a dynamic load application.
Deflection Measurements	Three LVDTs at 120 degrees apart	Same as Dynamic Modulus Test	An LVDT hookup is necessary to measure the recovery of the specimen when the load is released.
Temperature	14, 40, 70, 100, and 130°F	To be determined	Initial investigation will perform tests at the same temperatures as those used for the dynamic modulus.
Specimen Compaction	Superpave Gyratory Compactor	Same as Dynamic Modulus Test	
Specimen Dimensions	100mm diameter, 150mm height	+Same as Dynamic Modulus Test	This size is based on the results of a comprehensive specimen size and geometry study conducted in NCHRP Project 9-19. Specimen fabrication procedures are described in NCHRP 1-37A Draft Test Method DM-1.

* A screw type machine could be used for final field testing procedure protocol. The hydraulic type is being used in the laboratory for initial investigation.

+ Samples with diameters of 100mm will be used for the initial investigation. A 150mm diameter specimen would be used for final testing procedure protocol.

Figure 16 represents the type of load applied to specimens in a creep and recovery test. Figure 17 shows the measured creep and recovery deflection typical of viscoelastic materials under an applied constant stress. Figure 18 shows the creep compliance, D(t), which is calculated from the load magnitude and the measured deflection. Creep compliance, as measured by the static creep and recovery test can be represented by the Burger's constitutive model of viscoelastic behavior, discussed below.

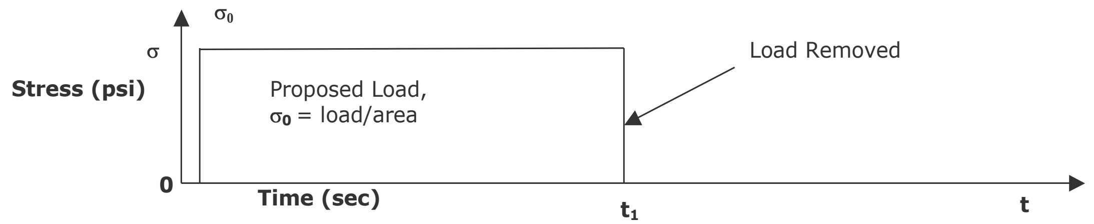


FIGURE 16. LOAD TYPE

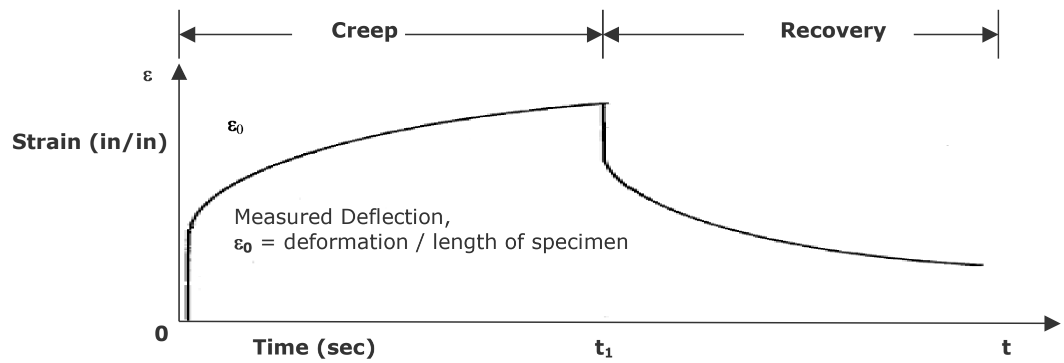


FIGURE 17. TYPICAL MEASURED DEFLECTION.

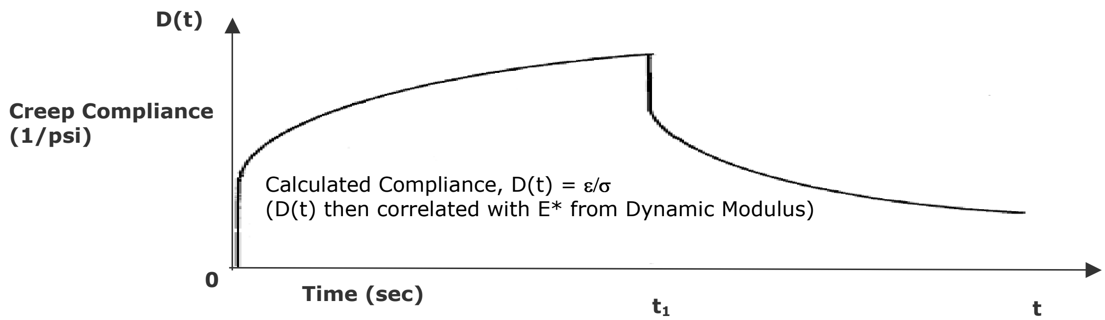


FIGURE 18. CALCULATED COMPLIANCE

3. INDENTATION TEST

The indentation test is another test in which creep compliance can be measured. It was proposed by the researchers that the indentation test has the potential to be used as a quality control test in the field (Mehta and Sukumaran, 2005). In the indentation test, as in the static creep and recovery test, a constant load is applied along the axis of a cylindrical specimen and the resulting deflection is measured. However, in the indentation test, a steel ball is used as the point of contact between the load and the specimen, rather than load plates. A schematic of the configuration is shown in Figure 19.

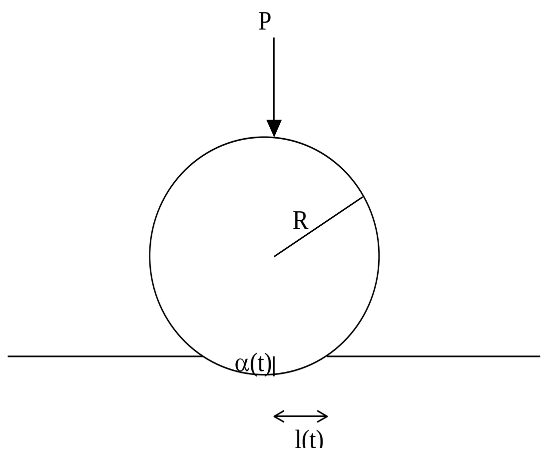


FIGURE 19. INDENTATION CONFIGURATION

Although a constant load is applied during the indentation test, it is not a constant stress test, unlike the creep and recovery test. As the deflection of the specimen increases under the constant load, the contact area between the ball and the specimen also increases, so the applied stress decreases over time. Initially, the contact area is very small which results in high initial stresses. Due to these high initial stresses, the asphalt concrete does not stay within the linear viscoelastic region. The implications of this fact are discussed later.

Simple extension creep compliance, D(t), is the compliance measured by the static creep and recovery test and is the ratio of strain to stress over time. The compliance measured by the indentation test, however, is the simple shear creep compliance, J(t), which is given, in terms of the indentation test parameters, by (Lee and Radok, 1960):

$$J(t) = \frac{16\sqrt{R}\,[\alpha(t)]^{3/2}}{3P_0 H(t)} \qquad (1)$$

where R is the radius of the sphere, $\alpha(t)$ is the central displacement at time t, P0 is the applied load, and H(t) is the Heaviside step function. The following relation can be used to convert the shear creep compliance to extension creep compliance:

$$D(t) \cong \frac{J(t)}{2(1+\nu)} \qquad (2)$$

where υ is Poisson's ratio, which was assumed to be 0.35, a common value for asphalt concrete mixtures.

The contact stress can also be calculated using the results of Lee and Radok (1960). They give the deflection of a point, w(r,t), at a distance r from the center of the indenting sphere at time t as:

$$w(r,t) = \frac{[l(t)]^2}{R} - \frac{r^2}{2R} \qquad \text{for } r \leq l(t) \qquad (3)$$

where R is the radius of the sphere and l(t) is the contact radius. So the central deflection, $\alpha(t) = w(0,t)$ is given by:

$$\alpha(t) = \frac{[l(t)]^2}{R} \qquad (4)$$

The contact stress, $\sigma(t)$, depends on the projected area of contact and was therefore calculated as:

$$\sigma(t) = \frac{P}{\pi R \alpha(t)} \qquad (5)$$

where P is the applied load.

As mentioned earlier, extension creep compliance can be converted to complex modulus, which correlates well with pavement performance. However, before the indentation test can be used to predict pavement performance in the field, it must be shown that the test yields extension creep compliance values which are affected by changes in volumetric properties of asphalt concrete in a manner similar to that of the creep compliance measured by the creep and recovery test. Therefore, one of the objectives of this study was to develop a correlation between the compliances obtained from the two tests.

SUMMARY

The dynamic modulus, which correlates well with rutting and fatigue, cracking, is the primary material characterization parameter for asphalt concrete mixtures in the ASSHTO mechanistic empirical pavement design guide. It has been shown that dynamic modulus tests can be performed within acceptable levels of variability; however the cost and time required for the test will likely prevent it from being widely adopted by the asphalt industry. Therefore, there is a need for a simple and cost effective method for determining the mechanical property of asphalt concrete at the plant and/or in the field. The creep and recovery or the flow test may have potential as a simpler alternative to the dynamic modulus test as a plant device since the results of each test can be theoretically interconverted. The indentation test may have potential as a field quality control device if it can be shown to be sensitive to critical volumetric properties of asphalt concrete.

APPENDIX B

RAP PLANT SURVEY

To study current stockpiling practices and plant operation survey questionnaire was developed which is attached as Appendix B1. Detailed information obtained from different plant is summarized in following section.

GLASSBORO HIGHWAY DEPARTMENT

On February 7, 2009, RAP was obtained from Glassboro Highway Department in Glassboro, New Jersey to conduct a pilot study. This was done in order to get practice with following the procedure for obtaining RAP and for finding any complications in how it is obtained. This would help potentially to eliminate any possible error that may be associated with visiting a larger asphalt plant unprepared. Approximately 55 kg of RAP, separated into 6 different samples, was taken out of 2 stockpiles, one with 6 month old asphalt and another with 5 year old asphalt. The manner in which the RAP was collected followed the process outlined in AASHTO T168-03. The only deviation from the procedure was how the samples were separated. The RAP was only split up into 6 different samples, 3 to 6 month old RAP and 3 to 5 year old RAP. Since this was a pilot study, the deviation was noted and would be corrected in the visits to the larger asphalt plants. In order to check for variability within the RAP stockpiles, the moisture content of each sample was calculated and can be found in Table 14.

TABLE 14. CALCULATED MOISTURE CONTENTS OF RAP SAMPLES

RAP Sample	Moisture Content (%)
6 month old	
1	4.0
2	3.92
3	4.01
Average	3.98
Deviation	0.049
COV (%)	1.23
5 year old	
1	4.14
2	4.09
3	4.61
Average	4.28
Deviation	0.287
COV (%)	6.71

From this table, it is shown that the moisture content of both ages of RAP did not differ significantly. The deviation of the 6 month old and 5 year old RAP was reasonable small which shows small variability throughout the stockpiles. The detailed survey from the plant has been shown in Table 15.

TABLE 15. PLANT SURVEY DETAIL FOR GLASSBORO HIGHWAY DEPARTMENT

Number of workers on site	0-49
Type of Plant	Batch
No of Cold feed bins	2
Annual Tonnage of RAP	400-599 thousand
Height of Tallest RAP stockpile	4-5 ft
Type of Storage of Pile	Separated Pile
Description of separated stockpile	Separated into two categories: Sift millings to 1.5 in, Unsifted millings up to 4 in
Type of Pile Storage Area	Paved surface area
Stockpile Drainage to prevent segregation	Sufficient
Method to determine Asphalt Content	Ignition Method
Type of RAP	Crushed
Size of Crushed RAP	1.5 inches
Quality Control Test performed on field	No QC test are performed

WELDON MATERIAL'S WATCHUNG QUARRY

On 18th March 2009 research team with Mr. Robert Sauber from NJDOT visited Weldon material's Watchung quarry located at Watchung, New Jersey. The purpose of this plant visit was to survey plant operation and obtains RAP samples for further evaluation.

Plant operation was studied by filling out a standard survey sheet. The Weldon plant has around 50 to 99 employees with 6 to 10 lab technician. RAP mix is stored in two RAP cold feed bins. At the plant asphalt mix testing, gradation and moisture content tests can be carry out for quality control. Generally one test per 499 ton or less RAP sample is carried out but this frequency also depends upon season of the year and current RAP use (ongoing project of plant). The asphalt content of samples is determined by ignition method and for quality control, moisture content and gradation checks are carried out at the plant.

Weldon plant receives less than 199 thousand ton of RAP annually. RAP entry to plant is done through either by hot elevator (batch) or by outer drum (continuous). Single stockpile of crushed RAP (0.5 inch sieve) is taller than 11 feet. Stockpile has sufficient drainage provision to prevent segregation of RAP. Samples are obtained from Weldon stockpile as per sampling method mentioned in literature review and stored in three different bins.

TRAP ROCK INDUSTRIES

On March 18, 2009 research team had visited the plant. The plant had a huge basalt quarry of 2200 acres. According to the QC manager, Trap Rock had capacity to produce any amount of RAP required by the client. They had stockpiled milling surface RAP and the rest of the RAP for example RAP from parking lot, from the base of the pavements, etc separately. The slope of the RAP pile was maintained such that the moisture content of the aggregate did not exceed 5%. According to the QC manager, the binder content in the RAP is in the range of 5-10% as tested by them on site by ignition method. In the past they have used the RAP up to 30% and they had observed satisfactory performance. The detailed survey from the plant have been tabulated below (Table 16):

TABLE 16. PLANT SURVEY DETAIL FOR TRAP ROCK INDUSTRIES

Number of workers on site	100-150
Number of lab technicians	6-10
Type of Plant	Continuous and Batch
Batch Entry	Hot Elevator
Continuous Entry	Mid Drum
On Site Lab Facility	Yes
On –Site Lab testing	Only Mixture Testing/No binder Testing
No of Cold feed bins	2
Annual Tonnage of RAP	As per demand
Height of Tallest RAP stockpile	11feet
Type of Storage of Pile	Separated Pile
Type of Pile Storage Area	Sloped Surface
Stockpile Drainage to prevent segregation	Sufficient
Method to determine Asphalt Content	Ignition Method
Type of RAP	Crushed
Size of Crushed RAP	0.5- 0.75 inches
Quality Control Test performed on field	Ignition Oven Fines Correction Moisture Content Gradation

Rowan University
201 Mullica Hill Road Glassboro, NJ 08028 • Phone/856.256.4000

Plant Owner	
Location	
Surveyor(s)	
Person Surveyed	
Date	
Email	
Phone Number	

General Plant Questions

					Comments
What type of plant is this?	Continuous ☐		Batch ☐		
How many employees do you have?	0 to 49 ☐	50 to 99 ☐	100 to 199 ☐	> 200 ☐	
How many lab technicians do you have?	1 to 5 ☐	6 to 10 ☐	11 to 20 ☐	> 20 ☐	
Do you have an on-site lab to test asphalt binder or asphalt mix?	Asphalt Binder ☐		Asphalt Mix ☐		
→If so, where?					
→How often? (one test per how many tons)	< 499 ☐	500 to 999 ☐	1000 to 1999 ☐	> 2000 ☐	
How many RAP cold feed bins are there?	0 ☐	1 ☐	2 ☐	3 ☐	

RAP Practices and Procedures

					Comments
How is the RAP transported to the lab?					
What is the annual tonnage (in thousands) of RAP received?	< 199 ☐	200 to 399 ☐	400 to 599 ☐	> 600 ☐	

What is the height of the tallest RAP stockpile?	< 4 feet ☐	5 to 7 feet ☐	8 to 10 feet ☐	> 11 feet ☐	
What point of RAP entry is there?	Batch ☐		Continuous ☐		
→If batch, what type?	Pugmill ☐	Weigh Hopper ☐	Hot Elevator ☐		
→If continuous, what type?	Mid Drum ☐	Behind Burner ☐	Outer Drum ☐	Second Drum ☐	
How is the RAP stored?	Single Stockpile ☐		Separated Stockpile ☐		
→If separated, explain this procedure					
→If separated, what type of storage area is there?	Sloped Surface ☐	Paved Surface ☐	Under Cover ☐	Other ☐	
Do stockpiles have sufficient drainage to prevent segregation?	Yes ☐		No ☐		
How is the AC content determined?	Ignition ☐	Centrifuge ☐	Vacuum ☐	Reflux ☐	
Do you crush RAP?	Yes ☐		No ☐		
→If yes, to what size?	< 0.50 inch ☐	1.00 inch ☐	1.50 inches ☐	> 1.50 inches ☐	
Please check, if any, the quality control tests conducted on RAP. Also list any other tests in the comments section	Ignition Oven ☐ Moisture Content ☐	Extraction Recovery ☐ Gradation ☐	Fines Correction ☐ Other ☐		

PLANT GRADING SYSTEM

A grading system is to be developed to determine the allowable RAP percentages for each plant in New Jersey. This will be done through the use of a tiered system dependent on aggregate properties, binder properties, and gradation. This grading system will work in conjunction with the survey set up for the plants on stockpiling practices.

Studies have shown that asphalt content is a vital component to the performance of RAP in HMA. Due to this, Maryland has developed a graph, shown in Figure 20, that shows a correlation between the maximum allowable RAP contents and variability of asphalt content within a stockpile. Our research group is currently in the process of contacting the Maryland DOT for the research behind this correlation.

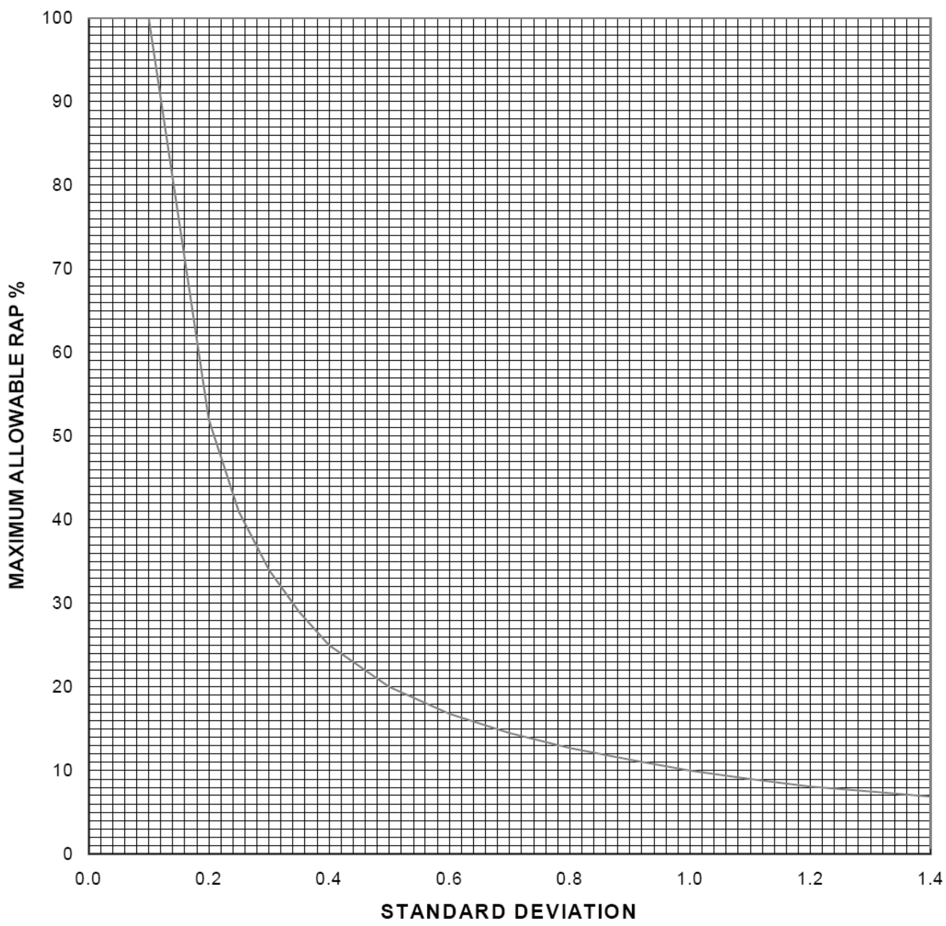


FIGURE 20. MAXIMUM ALLOWABLE RAP VS. STANDARD DEVIATION OF ASPHALT CONTENT (MDOT 1999)

A maximum of 50% of allowable RAP has been set in attempt to eliminate problems during processing RAP at asphalt plants. If a standard deviation is less than 0.2, it will still have an allowable RAP percentage of 50%.

This maximum RAP percentage value would be the starting percentage used in this grading system. Once this percentage is found, another set of deductions will be added for the variability of different RAP properties. This step is insignificant if the allowable RAP percentage determined from Figure 20 is 15% or lower. These deductions are based off of studies done from NAPA, AASHTO, and the USDOT on the effects of certain properties with the use of high percentages of RAP. In their book, Designing HMA Mixtures with High RAP Content (Newcomb, 2007), they have listed the importance of each property ranging from high to low. These ranges have been quantified into percentages that could be deducted from the starting allowable RAP Percentage. These values can be found in Table 17.

TABLE 17. LIST OF RAP VARIABILITY FACTORS WITH IMPACT ON GRADING

RAP Variability Factors	**Importance**	**Grading Impact (Concept ONLY)**
AC Content	High	From Equation Gives Starting Allowable RAP Percentage
		Max Score
Gradation	High	45%
CAA	Low	5%
FAA	Low	5%
F&E	Low	5%
Rotational Viscometer	Med	20%
DSR (unaged)	Med	20%

As of now, these numbers are only representing the concept of the grading system. They are only based on the importance given from the book discussed earlier. As more research is done on the effects of each of these properties, these numbers will be altered to match the results found. The final RAP percentage after all the deductions will be the final allowable RAP percentage for this plant. This system will coexist with a tiered system with a given set of criteria for different RAP percentages. This will help to determine which plants will be able to output a given RAP percentage. The criteria of this tiered system will also alter slightly as more research is done in this project. The concept of this tiered system is shown in Table 18.

TABLE 18. CONCEPT OF TIERED HIERARCHY CHART

Grading Tiers	Criteria	Maximum Allowable RAP
1	Asphalt Content Deviation ($x<0.3$) Gradation (Meets all control points) Aggregate Properties (Little to No Variability) Binder Properties (Little to No Variability)	50%
2	Asphalt Content Deviation ($0.3<x<0.4$) Gradation (Meets all control points) Aggregate Properties (Little to No Variability) Binder Properties (Small Variability)	35%
3	Asphalt Content Deviation ($0.4<x<0.7$) Gradation (Meets all control points) Aggregate Properties (Medium Variability) Binder Properties (Small Variability)	20%
4	Asphalt Content Deviation ($x>0.7$) Gradation (Doesn't meet control points) Aggregate Properties (Large Variability) Binder Properties (Large Variability)	15%

The tiered system as of now has criteria that specify three types of variability; large, medium, and little to none. Large variability would classify a standard deviation of a property coming very close to unacceptable. Little to no variability would classify a standard deviation of a property coming very close to zero. Medium variability would classify standard deviations between the large and small variability. These classifications will become more detailed as more research is done showing allowable standard deviation ranges for each property. This tiered system will also produce a final percentage of RAP allowed for the plant. The lower score of the tiered and grading systems will be chosen as the final plant allowable RAP percentage. It is important to have two tiered system to prevent the possibility of RAP being used that does not pass a current NJDOT standard. An example of this is the gradation of the RAP. If the gradation of the RAP does not meet or come close to the control points set by NJDOT, the deductions from the grading system would only reduce the allowed amount of RAP by 14%; however, this may put the entire HMA mix in danger of not meeting the NJDOT specifications. The second tiered system accounts for this by not allowing a gradation that doesn't meet NJDOT standards to only be able to use the minimum allowable RAP of 15%. These both assures the RAP HMA mix to meet NJDOT specifications while applying a safety factor.

A mock trial will be discussed now showing how this grading system works.

Step 1

Given from binder testing

Asphalt content standard deviation = 0.2

From Figure 20, the allowable RAP percentage is found to be 50%

Step 2

Deductions from variability in stockpiles (Grading System)

Given from testing

Gradation = Meets all control points

Aggregate Properties = Little to No Variability

Binder Properties = Small variability

TABLE 19. RESULTS FROM RAP TESTING

RAP Variability Factors	**Grading Impact**	
AC Content	From Equation Gives Starting Allowable RAP Percentage	
	Max Score	**Plant Score**
Gradation	45%	45%
CAA	5%	5%
FAA	5%	5%
F&E	5%	4%
Rotational Viscometer	20%	15%
DSR (unaged)	20%	16%
	Final Plant Score	90%

Gradation = Meets all control points

Aggregate Properties = Little to No Variability

Binder Properties = Small variability

From Table 19, the maximum allowable RAP percentage that could be used is calculated to be:

50% x 91% = **45%** **(Grading System)**

Classification: Tier 1

Step 3

Determine Maximum Allowable RAP Percentage Using Tiered System

From Table 18, the RAP testing passes all criteria for Tier 2, but not for Tier 1 because of the small variability in the binder properties

(Tier System) **Classification: Tier 2**

Therefore, the asphalt plant falls under tier 2 with a maximum allowable RAP of 40%.